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(U) This manual provides the recovery system engineer in Government and industry with tools to evaluate, select, design, test, manufacture, and operate parachute recovery systems. These systems range from simple, one-parachute assemblies to multiple-parachute systems, and may include equipment for impact attenuation, flotation, location, retrieval, and disposition. All system aspects are discussed, including the need for parachute recovery, the selection of the most suitable recovery system concept, a computerized approach to parachute performance, force and stress analysis, geometric gore design, component layout, material selection, system design, manufacturing, and in-service maintenance.

(U) The experienced recovery system engineer will find this publication useful as a technical reference book; the recent college graduate, a textbook for learning about parachutes and parachute recovery systems; and the technician with extensive practical experience, an engineering textbook that includes a chapter on parachute-related aerodynamics. Emphasis is placed on aiding Government employees to evaluate and supervise the design and application of parachute systems.

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Parachute Recovery Systems Design Manual

Chapters 1 Through 4 Offprint

by
T. W. Knacke
Aerosystems Department

JULY 1985

NAVAL WEAPONS CENTER
CHINA LAKE, CA 93555-6001

Naval Weapons Center

AN ACTIVITY OF THE NAVAL MATERIAL COMMAND

FOREWORD

This Parachute Recovery System Design Manual will provide parachute system design engineers with up-to-date recovery system information, and personnel entering the parachute design field with an all-inclusive training resource.

The manual was initiated by the Aerosystems Department of the Naval Weapons Center, China Lake, California. It is an extension of parachute recovery system engineering courses conducted by the principal author, Theo W. Knacke, at the Naval Weapons Center, China Lake, California; the Naval Surface Weapons Center, White Oak, Silver Spring, Maryland; and the University of Minnesota, Minneapolis, Minnesota.

Donald Goodrich of the Aerosystems Department of the Naval Weapons Center served as project coordinator and contributed technically to this manual. Additional contributors from the Aerosystems Department and other organizations are mentioned in the appropriate chapters. Sandie Lane of the Aerosystems Department and Hal Kornell served as editors.

The manual will be revised periodically to include newly published data and to ensure the availability of the latest state-of-the-art technology.

The report was reviewed for technical accuracy by Donald Goodrich.

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CONTENTS

Chapter 1
INTRODUCTION

The purpose of this manual is to provide the recovery system engineer in Government and industry with tools to evaluate, select, design, test, manufacture, and operate parachute recovery systems. These systems range from simple, one-parachute assemblies to multiple-parachute systems, and may include equipment for impact attenuation, flotation, location, retrieval, and disposition. All system aspects are discussed, including the need for parachute recovery, the selection of the most suitable recovery system concept, a computerized approach to parachute performance, force and stress analysis, geometric gore design, component layout, material selection, system design, manufacturing, and in-service maintenance.

The experienced recovery system engineer will find this publication useful as a technical reference book; the recent college graduate, a textbook for learning about parachutes and parachute recovery systems; and the technician with extensive practical experience, an engineering textbook that includes a chapter on parachute-related aerodynamics. Emphasis is placed on aiding Government employees to evaluate and supervise the design and application of parachute systems.

1.1 Concept

The parachute recovery system concept uses aerodynamic drag to decelerate people and equipment moving in air from a higher velocity to a lower velocity and to a safe landing, if required. This lower velocity is known as rate-of-descent, landing velocity, or impact velocity, and is determined by the following requirements: (1) landing personnel uninjured and ready for action, (2) landing equipment and air vehicles undamaged and ready for use or refurbishment, and (3) impacting weapons at a preselected angle and velocity.

The recovery cycle may include use of impact attenuation, flotation, and location equipment; retrieval by aircraft, boat, or ground vehicle; and delivery to an area for refurbishment and reuse.

Parachute recovery systems are required for personnel aircraft emergency escape, air drops of troops and supplies, stabilization and retardation of ordnance, recovery of targets, sport jumping, and similar applications. Optional uses include in-flight and landing deceleration of aircraft; recovery of missiles, spacecraft, and rockets; stabilization of falling bodies; and numerous other uses.

1.2 Content

The manual will contain 16 chapters. Chapters 1 through 4 are described here. References are provided at the end of each chapter.

Chapter 1, Introduction, defines the purpose of the manual. Chapter 2, Parachute Recovery System Definition and Description, discusses the concept of a parachute recovery system, its subsystems, and components. The primary applications of parachutes and parachute recovery systems used in the military and civilian sectors are listed, and the present and projected future performance boundaries of parachutes are shown. Design criteria are included for the selection of parachute systems with regard to reliability, performance, reuse, and other parameters.

Chapter 3, Units of Measurement, Technical Tables, and Symbols, introduces the English system and the System International (metric) of measurement, and contains tables for converting from one to the other. The technical tables list the properties of the atmosphere, versus altitude, in which parachutes operate, and the dynamic pressure in relation to Mach number, altitude, and airspeed. The chapter concludes with a list of the symbols used and recommended for parachute recovery system engineering.

Chapter 4, Aerodynamics as Related to Parachutes, is a short course in aerodynamics. It includes a discussion of the properties of the atmosphere, Reynolds and Mach numbers, continuity law and Bernoulli equations, Newton's three laws of motion, forces acting on bodies moving in air, and wind tunnel testing.

Chapters to be published later will include:

5. Parachute Characteristics
6. Design of Parachute Assemblies and Components
7. Bioengineering Aspects of Personnel Recovery
8. Parachute Textile Materials
9. Parachute Hardware
10. Computer Approach to Parachute Recovery Systems Design
11. Parachute Recovery Systems Design
12. Parachute Recovery Systems Application
13. Landing and Post-Impact Operations
14. Testing and Qualification
15. Manufacturing and Quality Control
16. Maintenance and Operation.

An appendix will contain a glossary of terms.

Chapter 2

PARACHUTE RECOVERY SYSTEM DEFINITION AND DESCRIPTION

Section 2.1, Parachute Recovery System Definition, defines the concept of a parachute recovery system with its assemblies and components. It proposes a common terminology and shows the typical breakdown structure of a parachute recovery subsystem used for an air vehicle primary system. Section 2.2, Parachute Recovery System Applications, lists the large variety of parachute applications in the field of aircraft escape and deceleration, air vehicle recovery, ordnance retardation, air drop of personnel and equipment, and commercial applications. Section 2.3, Parachute Recovery System Boundaries, shows the required velocity-altitude performance envelopes for different parachute applications and presents parachute performance boundaries. Section 2.4, Parachute Recovery System Design Criteria, provides design criteria useful for a comparative analysis of parachute recovery systems; a proposed evaluation scheme for specific applications is also included.

2.1 Parachute Recovery System Definition

Defining the components and terminology of a parachute recovery system will help to avoid misunderstandings between Government agencies, prime contractors, and subcontractors.

Although a parachute recovery system is a subsystem or even a subsubsystem of a prime system, as shown in Figure 2-1, common usage refers to all parachute recovery subsystems and assemblies as systems. Figure 2-1 also shows the typical breakdown structure of a target drone recovery system containing, besides the parachute recovery system, sequencing, impact attenuation, flotation, location, retrieval, and docking equipment.

Many parachute recovery systems contain fewer than the number of components listed in Figure 2-1. For example, an aircraft landing deceleration parachute system consists of a compartment in the aircraft, with door actuators and the parachute disconnect mechanism, and, separately within the compartment, a parachute assembly comprising an ejectable pilot chute, pilot-chute bridle, brake parachute, brake-parachute deployment bag, and riser with disconnect clevis.

Figure 2-2 is a schematic of a typical ejection seat parachute assembly with descriptive nomenclature. Many variations of the assembly are possible; i.e., independent main parachute deployment, the possibility of stabilized, high altitude descent on the drogue chute, seat stabilization by attitude sensors and Reaction Control System (RCS), velocity-altitude control of the parachute deployment sequence, and man-seat separation. The variations may result in more, or fewer, components and different component arrangements.

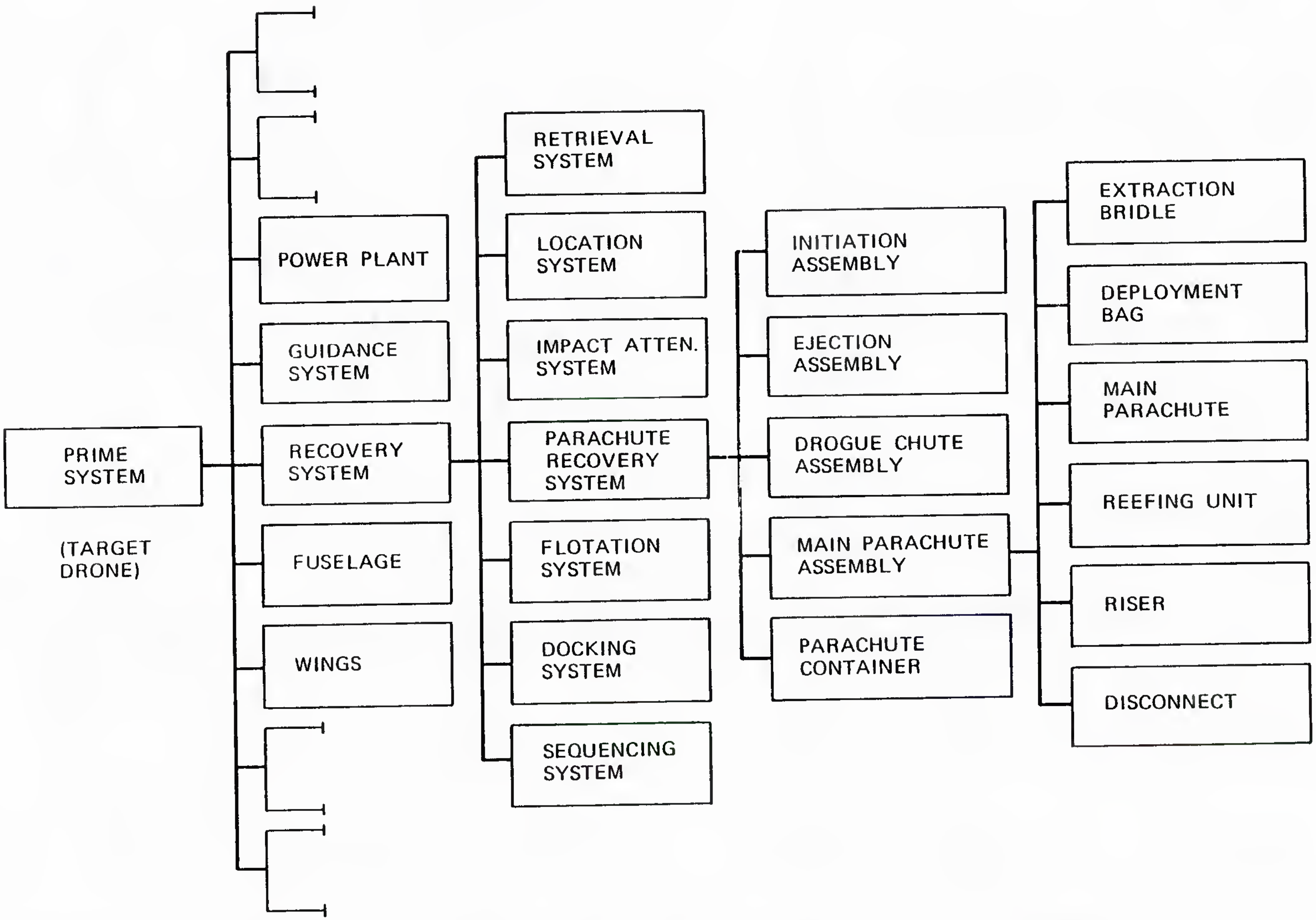
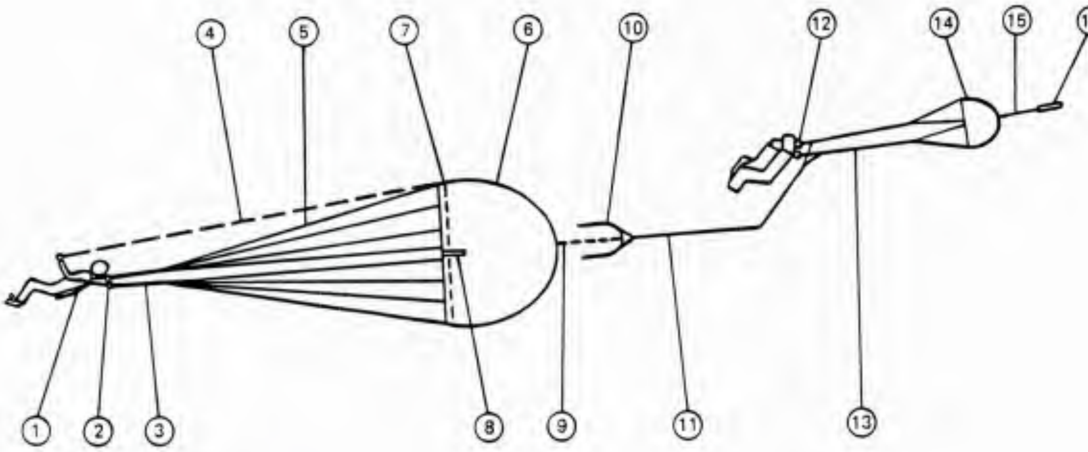


FIGURE 2-1. System Integration of a Parachute Recovery System and Components.



1 HARNESS
2 PARACHUTE DISCONNECTS (2)
3 RISERS (2)
4 CONTROL LINES (2)
5 SUSPENSION LINES
6 CANOPY
7 REEFING LINE AND RINGS
8 REEFING LINE CUTTERS
9 BREAK CORD
10 MAIN PARACHUTE DEPLOYMENT BAG
11 DEPLOYMENT BAG BRIDLE
12 DROGUE CHUTE DISCONNECTS
13 DROGUE CHUTE BRIDLES
14 DROGUE CHUTE
15 EXTRACTION BRIDLE
16 DROGUE GUN SLUG
17 EJECTION SEAT

1 TO 11 MAIN PARACHUTE ASSEMBLY
12 TO 16 DROGUE CHUTE ASSEMBLY

FIGURE 2-2. Schematic and Nomenclature of a Typical Ejection Seat Parachute Assembly.

2.2 Parachute Recovery System Applications

The first recorded development and application of parachute-type devices involved the lowering of animals, and occasionally humans, during fairs and carnivals in fourteenth- and fifteenth-century Siam and China. Parachute development in Europe and the United States began in the eighteenth century for use in exhibits and shows. The first application of parachutes for saving the lives of balloonists and aviators occurred during World War I. Since that time, parachutes have been used for the rescue of aviators, for premeditated jumps of military and civilian personnel, for sport jumpers, smoke jumpers, and paramedic jumpers.

An air drop of military personnel and equipment is the final phase of transport to a theater of operation. Personnel and equipment must land uninjured, undamaged, and ready for action or use.

Aircraft inflight and landing deceleration involves termination of dangerous flight maneuvers, such as spin, deep stall and high speed flutter. In these cases, the parachute is disconnected after the aircraft reaches a controlled flight attitude. Many military and some civilian aircraft use parachutes as landing brakes. This shortens the landing roll, and saves tires and brakes.

Many ordnance devices, such as bombs, mines, torpedoes and submunitions, are parachute-retarded to let the aircraft escape the effective range of the weapon, to stabilize and retard the weapon prior to water entry, to obtain antiricochet impact angles, and to obtain a desired splinter distribution pattern after impact.

Air vehicle recovery includes termination of flight, and recovery for reuse of targets, unmanned vehicle systems, booster rockets, and manned and unmanned spacecraft. Some of these are recovered by the Midair Retrieval System (MARS).

Parachutes are also used to decelerate high-speed land vehicles, rescue speed-boat crews, and decelerate ships. Figure 2-3 lists today's primary parachute applications.

PERSONNEL

1. PERSONNEL EMERGENCY
2. TRACTOR ROCKET ESCAPE SYSTEM
3. CAPSULE AND EJECTION SEAT STABILIZATION AND DECELERATION
4. RESCUE MISSIONS
5. SPORT JUMPING
6. SMOKE JUMPERS

AIRDROP

1. PARATROOPERS
2. ARMY COMBAT AND ENGINEERING EQUIPMENT
3. AERIAL RESUPPLY
4. SURVIVAL EQUIPMENT

AIRCRAFT DECELERATION

1. APPROACH AND LANDING
2. SPIN RECOVERY
3. INFLIGHT DECELERATION
4. HIGH-SPEED EMERGENCY

AIR VEHICLE RECOVERY

1. MISSILE/DRONE/UVS RECOVERY FOR REUSE, COMPONENT ANALYSIS, AND RANGE SAFETY
2. SOUNDING ROCKETS AND RE-ENTRY VEHICLES
3. MANNED/UNMANNED SPACECRAFT
4. BOOSTER

ORDNANCE RETARDATION

1. BOMB/MINE/TORPEDO RETARDATION
2. FLARES
3. SUBMUNITION
4. SONAR BUOYS
5. ECM/SENSOR

SPECIAL

1. AIR-TO-AIR RETRIEVAL
2. GROUND-TO-AIR RETRIEVAL
3. LAND/WATER SURFACE VEHICLE RETARDATION

FIGURE 2-3. Parachute Applications.

2.3 Parachute Recovery System Boundaries

The application range of parachutes with regard to velocity and altitude was closely associated with the speed and altitude capability of aircraft until the 1950s. A research program conducted in the late 1940s and early 1950s established that parachutes could be used at supersonic speeds; parachutes developed specifically for supersonic application followed. Today, in 1984, parachutes have been used successfully at speeds in excess of Mach 4.0, at altitudes up to the limits of the atmosphere, at dynamic pressures to 15,000 psi, and to recover a rocket booster weighing 185,000 pounds. Figure 2-4 gives the required parachute performance envelopes for different applications.

Figure 2-5 shows the approximate velocity and altitude boundaries of parachute systems that are presently in service or have been tested experimentally. Boundary limits are moved upward and outward as new materials are introduced that shift the aerodynamic heating limit to higher temperatures and make possible the recovery of heavier weight vehicles. Successful landings on the planet Mars have been made, and vehicle landings by parachute on the planets Venus and Jupiter are in preparation.

It is valid to state that the development of parachutes will keep pace with the development and the velocity range of new vehicle applications for land, sea, and air.

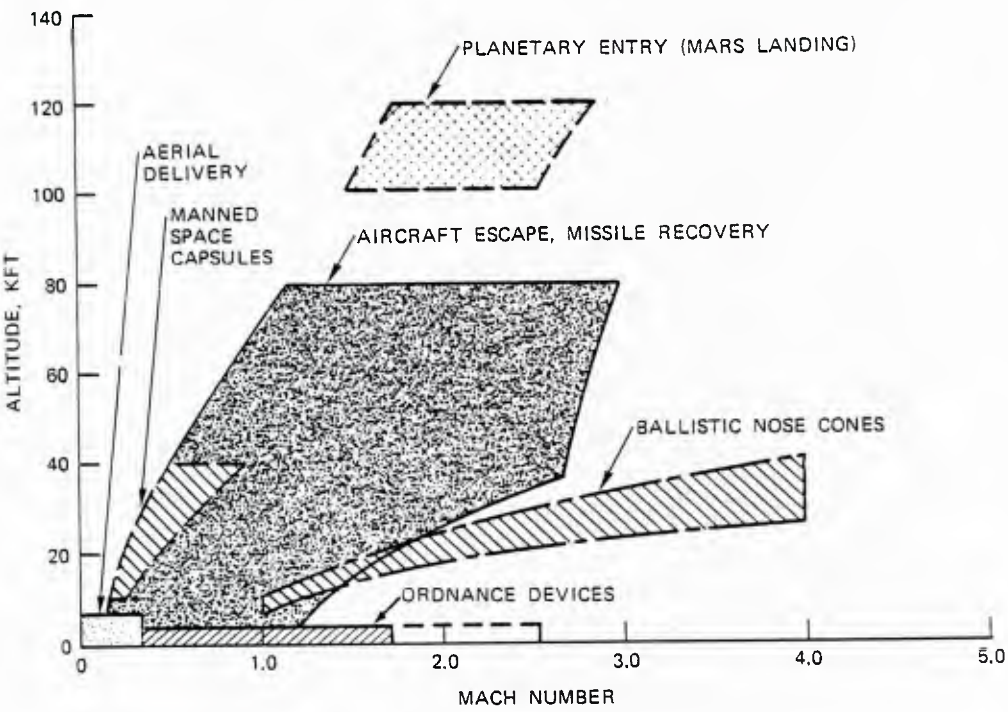


FIGURE 2-4. Parachute Performance Envelopes.

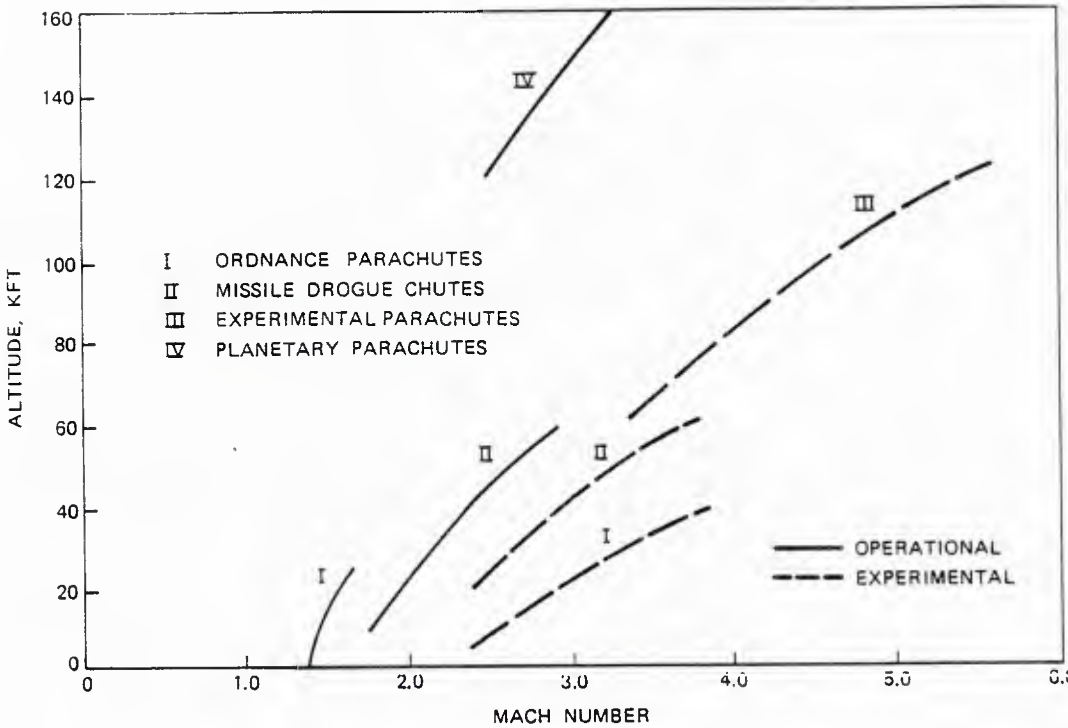


FIGURE 2-5. Aerodynamic Decelerator Performance Range (1984).

2.4 Parachute Recovery System Design Criteria

Prerequisites for the design of a parachute recovery system are an understanding of the purpose of the system and its requirements, and a clear definition of the design criteria governing system and component selection. Figure 2-6 lists typical design criteria.

System reliability will always be of utmost importance. Parachute recovery systems have reached a high degree of reliability, as documented by the 31 consecutive, successful, manned spacecraft landings and the high reliability rate of paratrooper use. In complex systems, it is mandatory to analyze and review all aspects and components of the total recovery system cycle. Failure to totally integrate the system can lead to the type of mishap experienced by space shuttle flight number seven in 1983, when a wrong sensor signal caused premature parachute disconnect, and the solid-fuel boosters were lost.

Weight and volume are important considerations. Parachute assemblies constitute approximately five percent of total vehicle weight for lightweight vehicles, and three to four percent for vehicles weighing several thousand pounds. A complete recovery system—including flotation, location, and retrieval assemblies—will weigh ten percent of the total vehicle weight, plus or minus two percent. The 560-pound Apollo parachute assembly that was carried around the moon and back to earth, where it was needed for landing, was a major expense in terms of weight, and much effort was dedicated to eliminating ounces to redue overall spacecraft weight.

- RELIABILITY
- STABILITY
- HIGH DRAG
- LOW-OPENING SHOCK
- HIGH-MACH CAPABILITY
- LOW WEIGHT AND VOLUME
- REPEATABILITY OF PERFORMANCE
- ENVIRONMENTAL ADAPTABILITY
- GROWTH POTENTIAL
- INDIFFERENCE TO DAMAGE
- SIMPLICITY OF DESIGN AND MANUFACTURING
- SIMPLICITY OF MAINTENANCE AND SERVICE

- LOW ACQUISITION COST
- LOW-LIFE CYCLE COST
- WEIGHT EFFICIENCY $\frac{(C_D \cdot S)_o}{W_P}$
- VOLUME EFFICIENCY $\frac{(C_D \cdot S)_o}{V_P}$
- COST EFFICIENCY $\frac{(C_D \cdot S)_o}{\$}$

$(C_D \cdot S)_o$	PARACHUTE DRAG AREA – FT^2
W_P	PARACHUTE WEIGHT = LB
V_P	PARACHUTE VOLUME – FT^3

FIGURE 2-6. Parachute Design Criteria.

For aerial targets, the recovery system is used only for recovery and retrieval in the last minutes of the mission. Each pound saved in the recovery system will benefit either the performance of the target, or permit an increase in payload.

The selection of the parachute frequently begins with the stability requirement. Aircraft deceleration parachutes, first stage drogue chutes, and most ordnance retardation parachutes require a high level of stability—a requirement that automatically eliminates many high drag parachutes.

A final descent parachute, the high weight item in any recovery system, is selected generally from high drag, solid textile parachutes. This results in parachutes of the smallest diameter, with concomitant low weight and volume. Limited parachute oscillation (0 to 10 degrees) of large final descent parachutes may be acceptable or overcome by use of cluster parachutes.

A high drag coefficient is important in selecting the final descent parachute(s). However, a better evaluation criterion is the weight efficiency ratio, $(C_D \cdot S)_o/W_P$, which shows how much parachute drag area, $(C_D \cdot S)_o$, is produced per pound of parachute or parachute assembly weight, W_P. Where the cost of the parachute system may be higher than the cost of the payload (e.g., food or other low dollar-per-pound items), the deciding factor may be cost efficiency, $(C_D \cdot S)_o/\$$.

Low opening shock is a valid selection criterion for unreefed parachutes, but loses its significance for large, reefed parachutes where reefing controls the force-time history of the parachute opening process.

The importance of growth potential in design must be emphasized. Most air vehicles that are recovered by parachute grow in weight during the development cycle. This is due to design changes, changes in requirements, or, when in service, added payloads. An undamaged landing requires maintaining the rate-of-descent. This may mean increasing the size of the final descent parachute(s) with the concurrent increase in weight and volume of the parachute assembly. The parachute compartment size normally is fixed early in the design cycle of the vehicle, and cannot be enlarged. The use of low pressure packing, at the start of the design for the parachute assembly, allows storage of a larger parachute assembly later, when higher pressure packing can be incorporated. The use of high pressure packing at the outset eliminates this possibility.

Repeatability of parachute performance is important for aircraft landing deceleration parachutes that are used twenty-five to fifty times. Repeatability is also a requirement for ordnance parachutes where parachutes manufactured to the same drawing must provide the same ballistic trajectory.

Table 2-1 is a guide for rating performance characteristics for different applications. Each application and each designer may use different rating values, based on the special requirements of the particular application.

TABLE 2-1. Comparative Rating of Performance Characteristics for Various Parachute Recovery Systems Applications.

Performance characteristics	Application					
	Spacecraft landing	Airborne troops	A/C escape	A/C landing deceleration	Ordnance	Aerial resupply
Reliability of operation	3	3	3	2	3	2
Repeatability of performance	2	2	2	3	3	1
Reuse	0	3	0	3	0	3
Weight and volume	3	2	3	2	2	1
Stability	2	2	2	3	3	2
High drag	2	2	2	2	2	3
Low opening forces	1	3	2	3	2	3
Low maintenance/service	1	3	2	3	2	3
Cost	1	2	2	2	2	3

Legend:
3 = high importance
2 = medium importance
1 = low importance
0 = not applicable

2.5 List of References

The following unclassified reference material is recommended for individuals who wish to obtain a general knowledge of parachutes and parachute recovery system application, performance, design, and components.

2.1 H. W. Bixby, E. G. Ewing, and T. W. Knacke, *Recovery Systems Design Guide*, USAF report AFFDL-TR-78-151, December 1978, available from the National Technical Information Service, Springfield, Virginia 22161.

2.2 Anon., *Performance of and Design Criteria for Deployable Aerodynamic Decelerators*, USAF report ASD-TR-61-579, December 1963, available from the Defense Documentation Center, Cameron Station, Alexandria, Virginia 22314.

2.3 *USAF Parachute Handbook*, ATI 35532, revised March 1951.

2.4 *USAF Parachute Handbook, Second Edition*, WADC Technical Report 55-265, ASTIA Document AD 118036, December 1956.

Proceedings and papers of the American Institute of Aeronautics and Astronautics (AIAA) conferences on Aerodynamic Decelerators and Balloon Technology, as listed:

2.5 Proceedings of the Eighth Conference, Hyannis, Massachusetts, April 1984, available in report form from the AIAA, 1633 Broadway, New York, N.Y. 10019.

2.6 Papers of the Seventh Conference, San Diego, California, October 1981, available as individual paper reprints from the AIAA office, 1633 Broadway, New York, N.Y. 10019.

2.7 Proceedings of the Sixth Conference, Houston, Texas, March 1979, available in report form from the AIAA office.

2.8 Papers of the Fifth Conference, Albuquerque, New Mexico, October 1976, available as individual paper reprints from the AIAA office.

2.9 Papers of the Fourth Conference, Palm Springs, California, May 1973, available as individual paper reprints from the AIAA office.

2.10 Papers of the Third Conference, Dayton, Ohio, September 1970, available as individual paper reprints from the AIAA office.

2.11 Proceedings of the Second Conference, El Centro, California, September 1968, available as USAF report FTC-TR-69-11, Volumes I and II, from the Defense Technical Information Center, Cameron Station, Alexandria, Virginia 22314.

2.13 Proceedings of the "Symposium on Parachute Technology and Evaluation," El Centro, California, September 1964, available as USAF report FTC-TR-64-12 from the Defense Documentation Center, Cameron Station, Alexandria, Virginia 22314.

2.14 Proceedings of the annual SAFE (Survival and Flight Equipment) Symposia, covering all aspects of aircrew and cockpit bioengineering, aircrew escape, survival, and rescue. Yearly Proceedings are available from the SAFE office, 15723 Vanowen St., Box 246, Van Nuys, California 91406.

2.15 Lectures of the 1982 H. G. Heinrich Short Course on Parachute Systems Technology, University of Minnesota, Department of Aerospace Engineering, 110 Union Street, S. E. Minneapolis, Minnesota 55455.

2.16 Parachute Data Bank reports and other technical data, formerly stored by USAF Flight Dynamics Laboratory, Wright-Patterson AFB, Dayton, Ohio, now obtainable in microfilm or copy form from Sandia National Laboratories, Organization 1632, Albuquerque, New Mexico 87185.

Chapter 3

UNITS OF MEASUREMENT, TECHNICAL TABLES, AND SYMBOLS

This chapter contains measurement terminology, conversion tables, atmospheric properties, and symbols employed in the analysis and design of parachute recovery systems. The chapter includes:

3.1 Units of Measurement
3.2 Conversion Tables
3.3 Technical Tables
3.4 List of Symbols
3.5 List of References

Section 3.1 defines the units of measurement used in engineering in the United States. There are two systems, the English System, and the S.I. (System Internationale) or Metric System. Tables for converting from one system to the other are provided in Section 3.2. The physical properties of the atmosphere and dynamic pressure versus velocity and altitude are covered in Section 3.3. Section 3.4 lists the symbols and abbreviations used in parachute recovery system design and analysis. These agree with those listed in Navy manuals and the Air Force Recovery System Design Guide.

Data presented herein have been drawn from tables in the *U.S. Standard Atmosphere, 1976*, the *Metric Design Guide*, the Air Force *Recovery System Design Guide*, Navy manuals, and other sources, as referenced in Section 3.5.

3.1 Units of Measurement

3.1.1 Basic Units

	Metric		English	
Quantity	Symbol	Name	Symbol	Name
Length	m	meter	ft	foot
Mass	kg	kilogram	lb	pound
Time	s	second	s	second
Temperature	K	kelvin	R	Rankine
Electric current	A	ampere	A	ampere

3.1.2 Derived Units

Quantity	Symbol	Name	Dimension
Force	N	newton	$kg \bullet m/s^2$
Pressure	Pa	pascal	N/m^2
Work, energy	J	joule	$N \bullet m$
Rate of energy	W	watt	J/s

The metric units of measurement defined in Sections 3.1.1 and 3.1.2 are used by physicists, but seldom by engineers who work with English units of measurement.

3.1.3 Engineering Units of Measurement

Length

One statute mile (mi) = 1,760 yards (yd) = 5,280 feet (ft).
One foot = 12 inches (in.).
One kilometer (km) = 1,000 meters (m).
One meter = 100 centimeters (cm).
One centimeter = 10 millimeters (mm).
One millimeter = 10,000 microns.
One meter = 10^3 millimeters = 10^7 microns = 10^{10} angstroms.

Area

One square mile (mi^2) = 640 acres = 3,097,600 square yards (yd^2).
One square yard = 9 square feet (ft^2).
One square foot = 144 square inches (in^2).
One square kilometer (km^2) = 1,000,000 square meters (m^2).
One square meter = 10,000 square centimeters (cm^2).
One square centimeter = 100 square millimeters (mm^2).

Volume

One cubic yard (yd^3) = 27 cubic feet (ft^3).
One cubic foot = 7.48 gallons (gal) = 1,728 cubic inches (in^3).
One cubic meter (m^3) = 1,000 liters (lt).
One liter = 1,000 cubic centimeters (cm^3) = 1,000 milliliters.
One cubic centimeter = 1,000 cubic millimeters (mm^3).

Weight

One English ton = 2,000 pounds (lb).
One pound = 16 ounces (oz).
One ounce = 437.5 grains (gr).
One metric ton = 1,000 kilograms (kg).
One kilogram = 1,000 grams (g).

Force

One pound force = 4.44822 newtons (N).
One kilogram force = 9.80665 newtons.

Pressure

One pound per square inch (psi) = 144 pounds per square foot (lb/ft^2).
One atmosphere (atm) = 14.696 psi = 29.921 inches of mercury (in. Hg).
One kilogram per square centimeter (kg/cm^2) = one technical atmosphere.
One pascal (Pa) = one newton per square meter (N/m^2).
Torr, millibar, and psi are used to define atmospheric pressure. See tables in Section 3.2 for conversion between units.

Power

One horsepower (HP) = 0.7457 kilowatt (kW) = 550 foot-pounds per second (ft-lb/s)
One metric horsepower = 75 kg-m/s = 0.9863 English horsepower.

Density

One pound per cubic inch (lb/in^3) = 1728 pounds per cubic foot (lb/ft^3).
One gram per cubic centimeter (g/cm^3) = one kilogram per liter (kg/lt) = one metric ton per cubic meter (ton/m^3).

Temperature

Absolute zero = zero degrees kelvin (°K) = −273.16 degrees Celsius (°C); or −459.67 degrees Fahrenheit (°F) = zero degrees Rankine (°R).

Velocity

One knot = 1 nautical mile per hour = 1852 meters per hour (m/h).
One mile per hour (mph) = 1.4667 feet per second (ft/s).
One kilometer per hour (km/h) = 0.27778 meter per second (m/s).

Acceleration

Acceleration is measured as velocity change per second.

3.2 Conversion Tables

Conversion Table 3-1 in this section is based on tables used in the aerospace industry, and has been updated with information contained in References 3.1 to 3.4. Table 3-2 provides a convenient method to convert temperature data from Fahrenheit to Celsius, or vice versa.

TABLE 3-1. Conversion of English System to Metric System.

To convert from	To	Multiply by
atmosphere	pounds per square inch	14.69601
	kilograms per square centimeter	1.0332
	technical atmosphere	1.0332
	millimeters mercury	760.0
	inches mercury	29.9213
	newton per square meter	1.01325
bar	kilograms per square centimeter	1.0197
	inches of mercury	29.531
	pascal	10^5
	atmosphere	0.9869
British thermal units (Btu)	foot-pounds	777.98
	kilogram-calories	0.25198
centimeters	inches	0.39370
	feet	0.032808
centimeters of mercury	inches of water	5.35239
	pounds per square inch	0.19337
cubic centimeters	liters	0.001
	cubic inches	0.06102
cubic feet	cubic inches	1,728.0
	cubic yards	9.0
	gallons	7.48052
	liters	28.31685
	cubic meters	0.02832
cubic feet per minute	cubic meters per minute	0.02832
cubic inches	cubic centimeters	16.38706
	liters	0.01639
	gallons	0.00433
cubic meters	cubic centimeters	10^6
	cubic feet	35.31445
	cubic yards	1.30794
	gallons	264.1776
cubic yards	cubic feet	27.0
	cubic meters	0.76456
degrees (arc)	radians	0.01745
dynes	grams (mass) x centimeters per second squared	1.0

TABLE 3-1. (Contd.)

To convert from	To	Multiply by
fathoms	feet meters	6.0 1.82880
feet	inches yards centimeters meters	12.0 3.0 30.48 0.3048
feet per minute	miles per hour kilometers per hour meters per second knots	0.01136 0.01829 0.00580 0.00987
feet per second	miles per hour kilometers per hour meters per second knots	0.68182 1.09728 0.30480 0.59249
foot-pounds	kilogram-meters	0.13826
foot-pounds per second	horsepower	1/550 = 0.00182
gallons	cubic inches cubic feet liters imperial gallons	231.04 0.13368 3.78540 0.83268
grams	ounces pounds milligrams kilograms	0.03528 0.00221 1,000.0 0.001
grams per cubic centimeter	kilograms per cubic meter pounds per cubic foot	1,000.0 62.42833
horsepower	foot-pounds per second kilogram-meters per second metric horsepower kilowatts British thermal units per second	550.0 76.04039 1.01387 0.7457 0.7068
horsepower, metric	kilogram-meters per second horsepower, English watts	75.0 0.98632 735.499
inches	centimeters	2.54

TABLE 3-1. (Contd.)

To convert from	To	Multiply by
inches of mercury	pounds per square inch	0.49116
	atmosphere	0.03342
	kilograms per square meter	0.03453
inches of water	inches of mercury	0.07349
	pounds per square inch	0.03609
joules	newtons × meters	1.0
	watt-seconds	1.0
	foot-pounds	0.73756
kilograms	pounds	2.20462
	grams	1,000.0
kilogram-meters	foot-pounds	7.23275
kilograms per cubic meter	pounds per cubic foot	0.06243
	grams per cubic centimeter	0.001
kilograms per square meter	pounds per square inch	0.00142
	inches of mercury	0.002896
	grams per square centimeter	0.1
	pounds per square foot	0.20477
kilometers	feet	3,280.839
	statute miles	0.62137
	nautical miles	0.53996
kilometers per hour	feet per second	0.91134
	miles per hour	0.62137
	knots	0.53996
	meters per second	0.27778
knots	nautical miles per hour	1.0
	feet per second	1.68781
	miles per hour	1.15078
	kilometers per hour	1.852
	meters per second	0.51444
liters	cubic centimeters	1,000.0
	cubic inches	61.02376
	cubic feet	0.03532
	gallons	0.26417
meters	inches	39.37008
	feet	3.28084
	yards	1.09361

TABLE 3-1. (Contd.)

To convert from	To	Multiply by
meters per second	feet per second	3.28084
	miles per hour	2.23693
	kilometers per hour	3.6
	knots	1.94384
microns	centimeters	0.0001
miles per hour	knots	0.86898
	feet per second	1.46667
	kilometers per hour	1.60934
	meters per second	0.44704
mills	inches	0.001
	millimeters	0.0254
nautical miles (U.K.)	feet	6,080.20
nautical miles (USN, Intl)	meters	1,852.0
	feet	6,076.1155
	statute miles	1.15078
newtons	kilograms × meters per second squared	1.0
	pounds force	0.22481
	kilogram force	0.10197
ounces	pounds	16.0
	grams	28.3495
pascals	newtons per square meter	1.0
	pounds per square foot	0.02082
	kilograms per square meter	0.10197
pounds	kilograms	0.45359
pounds force	newtons	4.44822
pounds per cubic inch	pounds per cubic foot	1,728.0
	grams per cubic centimeter	27.67974
pounds per square foot	inches of water	0.19242
	kilograms per square meter	4.88352
pounds per square inch	inches of water	27.7085
	atmosphere	0.06806
	kilograms per square meter	703.06687

TABLE 3-1. (Contd.)

To convert from	To	Multiply by
quarts	gallons cubic inches	4.0 57.75
radians	degrees	57.29578
radians per second	degrees per second revolutions per second	57.29578 0.15916
square centimeters	square inches	0.155
square feet	square centimeters	929.0304
square inches	square millimeters	645.16
square kilometers	square miles	0.38610
square meters	square yards	1.19599
square miles	square kilometers	2.58998
statute miles	feet nautical miles kilometers	5.280.0 0.86898 1.60934
tons, long	pounds kilograms	2,240.0 1,016.047
tons, short	pounds kilograms	2,000.0 907.1847
tons, metric	kilograms long tons short tons	1,000.0 0.98421 1.10231
torr	millimeters of mercury	1.0
watts	newtons $\times$ meters per second	1.0
yards	centimeters meters	91.44 0.9144

TABLE 3-2. Temperature Conversion Table.

To convert from Fahrenheit to Celsius, go from center column to left column. To convert from Celsius to Fahrenheit, go from center column to right column. Conversion formulas:

$$C = \frac{5}{9}(F\text{-}32);\ F = \frac{9}{5}C + 32$$

−100 to 25			26 to 61			62 to 97		
C.	F. C.	F.	C.	F. C.	F.	C.	F. C.	F.
−73	−100	−148	− 3.3	26	78.8	16.6	62	143.6
−68	− 90	−130	− 2.8	27	80.6	17.1	63	145.4
−62	− 80	−112	− 2.2	28	82.4	17.7	64	147.2
−57	− 70	− 94	− 1.6	29	84.2	18.2	65	149.0
−51	− 60	− 76	− 1.1	30	86.0	18.8	66	150.8
−46	− 50	− 58	− 0.6	31	87.8	19.3	67	152.6
−40	− 40	− 40	0.0	32	89.6	19.9	68	154.4
−34	− 30	− 22	0.5	33	91.4	20.4	69	156.2
−29	− 20	− 4	1.1	34	93.2	21.0	70	158.0
−23	− 20	14	1.6	35	95.0	21.5	71	159.8
−17.7	0	32	2.2	36	96.8	22.2	72	161.6
−17.2	1	33.8	2.7	37	98.6	22.7	73	163.4
−16.6	2	35.6	3.3	38	100.4	23.3	74	165.2
−16.1	3	37.4	3.8	39	102.2	23.8	75	167.0
−15.5	4	39.2	4.4	40	104.0	24.4	76	168.8
−15.0	5	41.0	4.9	41	105.8	25.0	77	170.6
−14.4	6	42.8	5.5	42	107.6	25.5	78	172.4
−13.9	7	44.6	6.0	43	109.4	26.2	79	174.2
−13.3	8	46.4	6.6	44	111.2	26.8	80	176.0
−12.7	9	48.2	7.1	45	113.0	27.3	81	177.8
−12.2	10	50.0	7.7	46	114.8	27.7	82	179.6
−11.6	11	51.8	8.2	47	116.6	28.2	83	181.4
−11.1	12	53.6	8.8	48	118.4	28.8	84	183.2
−10.5	13	55.4	9.3	49	120.2	29.3	85	185.0
−10.0	14	57.2	9.9	50	122.0	29.9	86	186.8
− 9.4	15	59.0	10.4	51	123.8	30.4	87	188.6
− 8.8	16	61.8	11.1	52	125.6	31.0	88	190.4
− 8.3	17	63.6	11.5	53	127.4	31.5	89	192.2
− 7.7	18	65.4	12.1	54	129.2	32.1	90	194.0
− 7.2	19	67.2	12.6	55	131.0	32.6	91	195.8
− 6.6	20	68.0	13.2	56	132.8	33.3	92	197.6
− 6.1	21	69.8	13.7	57	134.6	33.8	93	199.4
− 5.5	22	71.6	14.3	58	136.4	34.4	94	201.2
− 5.0	23	73.4	14.8	59	138.2	34.9	95	203.0
− 4.4	24	75.2	15.6	60	140.0	35.5	96	204.8
− 3.9	25	77.0	16.1	61	141.8	36.1	97	206.6

TABLE 3-2. (Contd.)

98 to 510			520 to 970			980 to 1000		
C.	F. C.	F.	C.	F. C.	F.	C.	F. C.	F.
36.6	98	208.4	271	520	968	526	980	1796
37.1	99	210.2	276	530	986	532	990	1814
37.7	100	212.0	282	540	1004	538	1000	1832
38	100	212	288	550	1022			
43	110	230	293	560	1040			
49	120	248	299	570	1058			
54	130	266	304	580	1076			
60	140	284	310	590	1094			
65	150	302	315	600	1112			
71	160	320	321	610	1130			
76	170	338	326	620	1148			
83	180	356	332	630	1166			
88	190	374	338	640	1184			
93	200	392	343	650	1202			
99	210	410	349	660	1220			
100	212	413	354	670	1238			
104	220	428	360	680	1256			
110	230	446	365	690	1274			
115	240	464	371	700	1292			
121	250	482	376	710	1310			
127	260	500	382	720	1328			
132	270	518	387	730	1346			
138	280	536	393	740	1364			
143	290	554	399	750	1382			
149	300	572	404	760	1400			
154	310	590	410	770	1418			
160	320	608	415	780	1436			
165	330	626	421	790	1454			
171	340	644	426	800	1472			
177	350	662	432	810	1490			
182	360	680	438	820	1508			
188	370	698	443	830	1526			
193	380	716	449	840	1544			
199	390	734	454	850	1562			
204	400	752	460	860	1580			
210	410	770	465	870	1598			
215	420	788	471	880	1616			
221	430	806	476	890	1634			
226	440	824	482	900	1652			
232	450	842	487	910	1670			
238	460	860	493	920	1688			
243	470	878	498	930	1706			
249	480	896	504	940	1724			
254	490	914	510	950	1742			
260	500	932	515	960	1760			
265	510	950	520	970	1778			

3.3 Technical Tables

3.3.1 Earth's Atmosphere

The planet Earth is surrounded by a blanket of gas pressing statically against its surface and making up its atmosphere. Atmospheric pressure, density, temperature, and the speed of sound vary with altitude.

Table 3-3 lists, versus altitude, the static pressure, p, in lb/ft^2, the density, ϱ, in slugs/ft^3, the temperature, T, in °F, and the speed of sound, C_s, in ft/s. These data are taken from Reference 3.4. The altitude scale is represented by a vertical on the earth's surface extending through the center of the earth. The data in Table 3-3 are averages, varying with seasonal weather changes and the fact that the earth is not a perfect sphere. Reference 3.4, which contains a detailed discussion of these variations, may be consulted for higher altitude data.

Pressure and density decrease gradually with altitude. At an altitude of approximately 275,000 feet, continuum flow gradually changes to molecular flow and, subsequently, atomic flow. Sustained flight of aircraft with air-breathing engines ceases to be practical at altitudes approaching 100,000 feet due to the low density of the atmosphere.

It is interesting to note that the temperature gradually decreases with altitude to 37,000 feet, remains constant to 65,000 feet, and then increases again. A second temperature reversal occurs at approximately 160,000 feet (Reference 3.4). Figure 3-1 shows the altitude dependency of temperature and speed of sound. The close relationship between temperature and speed of sound is discussed in Chapter 4.

The value, $1/\sqrt{\varrho/\varrho_0}$, permits the determination of rate-of-descent at any altitude. For example, a parachute with a sea level rate-of-descent, v_{e_0}, of 20 ft/s has a rate-of-descent, v_e, at 40,000 feet of $20 \cdot (1/\sqrt{\varrho/\varrho_0}) = 20 \cdot 2.0118 = 40.24$ ft/s.

Chapter 4 contains an explanation of the importance of dynamic pressure, q, in all aerodynamic calculations. Figure 3-2 gives dynamic pressure in psf in relation to altitude, Mach number, and true airspeed. These graphic values should be used only for preliminary calculations. Final dynamic pressure values should be calculated using the method shown in Chapter 4.

TABLE 3-3. Properties of Earth's Atmosphere Versus Altitude.

Altitude Z, ft	Pressure p, psf	Density ϱ, slugs/ft^3	$\frac{1}{\sqrt{\varrho/\varrho_0}}$	Temp T, °F	Speed of sound C_s, ft/s
0	2116.22	.237689-2	1.0000	59.000	1116.45
1000	2040.86	.230812	1.0148	55.434	1112.61
2000	1967.69	.224088	1.0299	51.868	1108.75
3000	1896.67	.217516	1.0453	48.303	1104.88
4000	1827.75	.211093	1.0611	44.738	1100.99
5000	1760.87	.204817	1.0773	41.173	1097.10
6000	1696.00	.198685	1.0938	37.609	1093.19
7000	1633.08	.192695	1.1106	34.045	1089.26
8000	1572.07	.186845	1.1279	30.482	1085.32
9000	1512.93	.181133	1.1455	26.918	1081.37

TABLE 3-3. (Contd.)

Altitude Z, ft	Pressure p, psf	Density ϱ, slugs/ft^3	$\frac{1}{\sqrt{\varrho/\varrho_0}}$	Temp T, °F	Speed of sound C_s, ft/s
0	2116.22	.237689-2	1.0000	59.000	1116.45
10000	1455.60	.175555-2	1.1636	23.355	1077.40
12000	1346.24	.164796	1.2010	16.231	1069.43
14000	1243.65	.154551	1.2401	9.107	1061.40
16000	1147.50	.144802	1.2812	1.985	1053.30
18000	1057.48	.135533	1.3243	−5.135	1045.15
20000	9732.75-1	.126726-2	1.3695	−12.255	1036.93
22000	8946.02	.118365	1.4171	−19.373	1028.65
24000	8211.72	.110435	1.4671	−26.489	1020.30
26000	7527.14	.102919	1.5197	−33.605	1011.89
28000	6889.64	.958016	1.5751	−40.719	1003.40
30000	6296.69-1	.890686	1.6336	−47.831	994.85
32000	5745.85	.827050	1.6953	−54.942	986.22
34000	5234.80	.766963	1.7604	−62.052	977.52
36000	4761.28	.710284	1.8293	−69.160	968.75
38000	4326.40	.646302	1.9177	−69.700	968.08
40000	3931.29-1	.587278-3	2.0118	−69.700	968.08
42000	3572.33	.533655	2.1105	−69.700	968.08
44000	3246.20	.484936	2.2139	−69.700	968.08
46000	2949.90	.440673	2.3224	−69.700	968.08
48000	2680.70	.400458	2.4363	−69.700	968.08
50000	2436.11-1	.363919-3	2.5556	−69.700	968.08
52000	2213.67	.330721	2.6809	−69.700	968.08
54000	2011.95	.300556	2.8121	−69.700	968.08
56000	1828.47	.273148	2.9499	−69.700	968.08
58000	1661.76	.248243	3.0943	−69.700	968.08
60000	1510.28-1	.225614-3	3.2458	−69.700	968.08
62000	1372.63	.205051	3.4046	−69.700	968.08
64000	1247.55	.186365	3.5713	−69.700	968.08
66000	1133.88	.169344	3.7464	−69.604	968.20
68000	1030.76	.153513	3.9348	−68.514	969.55
70000	9372.76-2	.139203-3	4.1322	−67.424	970.90
72000	8938.59	.132571	4.3388	−66.334	972.24
74000	8525.13	.126263	4.5550	−66.224	973.59
76000	7058.82	.103970	4.7813	−64.155	974.93
78000	6425.82	.943868-4	5.0183	−63.066	976.28
80000	5851.20	.857110	5.2659	−61.977	977.62
82000	5329.42	.778546	5.5255	−60.888	978.95
84000	4855.49	.707382	5.7968	−59.799	980.29
86000	4424.91	.642902	6.0805	−58.711	981.62
88000	4033.60	.584461	6.3771	−57.623	982.95
90000	3677.88-2	.531480-4	6.6876	−56.535	984.28
92000	3354.42	.483433	7.0121	−55.447	985.61
94000	3060.2	.439851	7.3513	−54.359	986.93
96000	2792.56	.400305	7.7059	−53.272	988.26
98000	2548.98	.364413-4	8.0762	−52.185	989.58
100000	2327.25	.331829	8.4631	−51.098	990.90

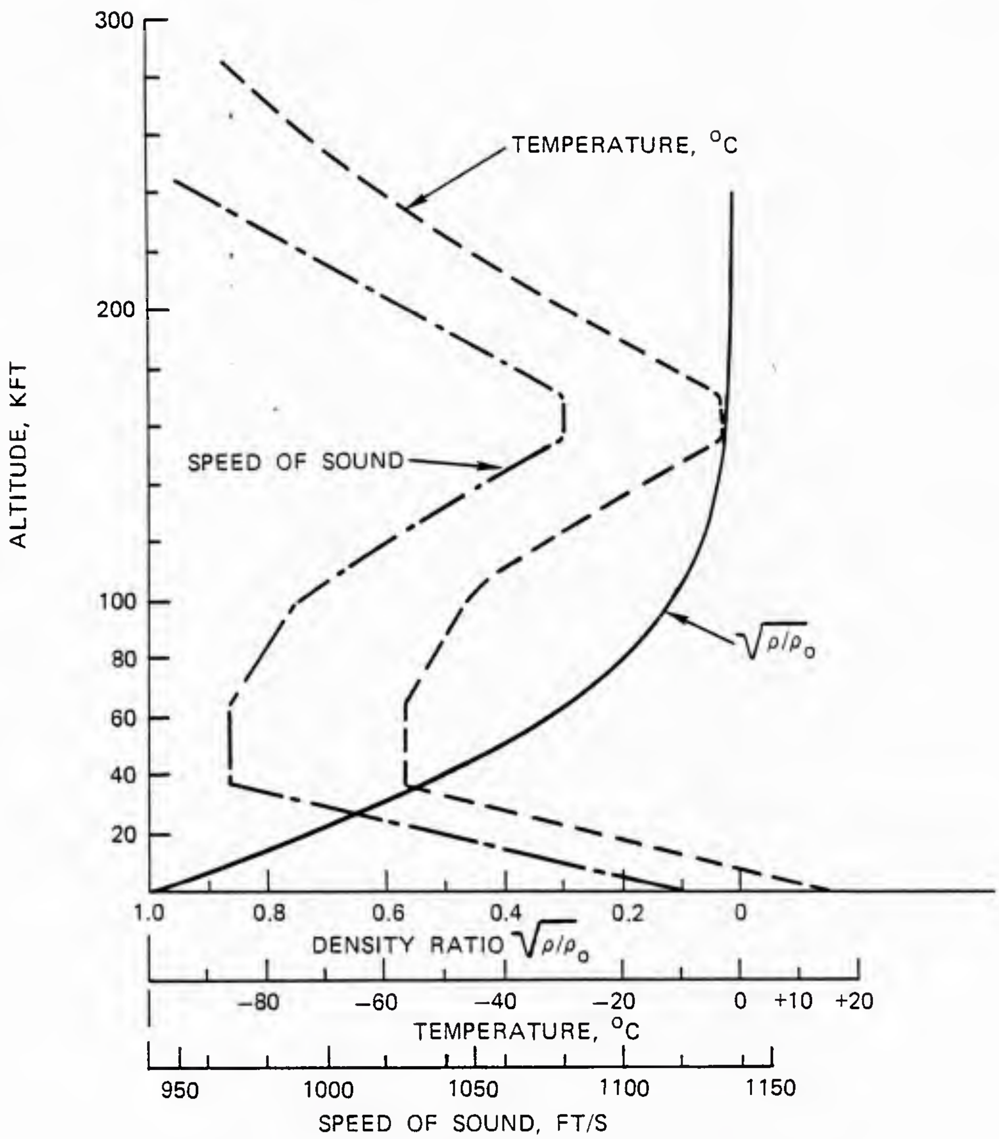


FIGURE 3-1. Density Ratio, Temperature, and Speed of Sound Versus Altitude (Reference 3.4).

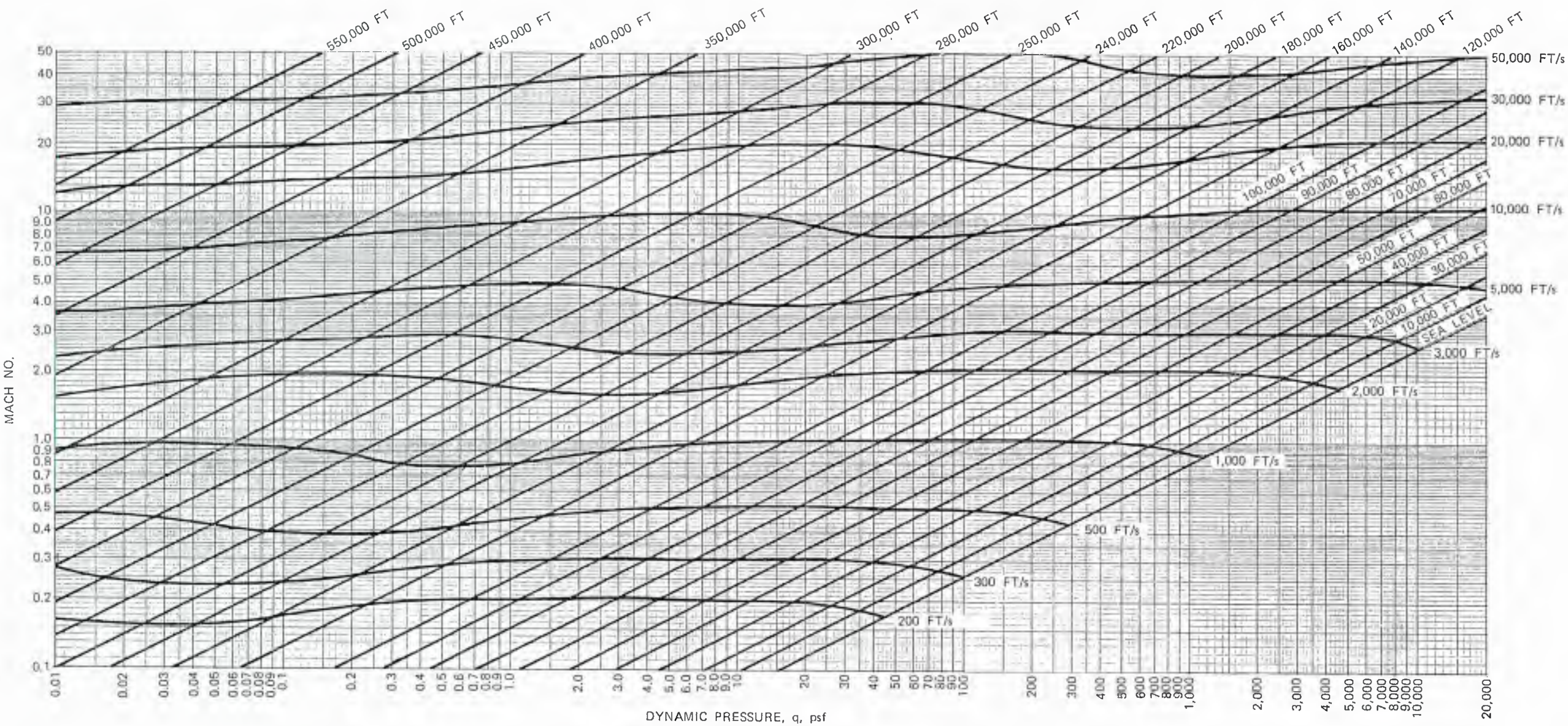


FIGURE 3-2. Dynamic Pressure Versus Altitude, Mach Number, and True Airspeed Velocity.

3.4 List of Symbols

A	Area
AR	Aspect ratio
a	Acceleration
b	Wing span
C	Coefficient, constant
C_A, C_R	Aerodynamic force coefficients
C_D	Drag coefficient
C_{D_C}	Drag coefficient of parachute cluster
C_{D_o}	Drag coefficient related to canopy surface area (S_o)
C_{D_p}	Drag coefficient related to inflated canopy area (S_p)
C_f	Coefficient of friction
C_L	Lift coefficient
C_m	Moment coefficient
C_N	Normal or side force coefficient
C_p	Pressure coefficient, specific heat
C_R	Resultant or radial force coefficient
C_x	Opening force coefficient (infinite mass)
c	Dimension of wing chord, factor related to suspension line convergence
C_s	Velocity of sound
C_DA	Forebody drag area
$(C_DS)_o$	Effective drag area of parachute related to canopy surface area (S_o)
$(C_DS)_P$	Parachute drag area, general
$(C_DS)_R$	Parachute drag area, reefed
D	Drag, diameter
D_F	Design factor
D_o	Nominal diameter of parachute canopy $= (4/\pi \cdot S_o)^{1/2}$
D_p	Projected diameter of parachute canopy $= (4/\pi \cdot S_p)^{1/2}$
D_R	Diameter of reefing-line circle
D_v	Diameter of canopy vent
E	Young's modulus of elasticity
E_K	Kinetic energy
e	Strength loss factor due to abrasion, canopy gore width
e_s	Gore width at skirt of canopy
e_v	Gore width at vent of canopy
F	Force, structural load
F_c	Constant force, steady-state drag force
F_N	Normal force
F_o	Parachute opening force
F_x	Parachute maximum opening force
F_R	Reefed opening force
F_S	Parachute snatch force
F_{ult}	Ultimate load
f	Unit stress, frequency, "a function of"
G	Load factor $= a/g$
g	Acceleration of gravity
g_o	Acceleration of gravity at sea level (MSL)
h	Height (general), height of canopy gore at any point
h_g	Height of canopy gore from vent to skirt

h_v	Height of vent
I	Impulse
i	Strength loss factor due to vacuum
K	Constant (general)
K_f	Dimensionless filling time parameter
k	Strength loss factor due to fatigue
L	Lift
L/D	Lift-to-drag ratio = glide ratio
l	Length (general)
l_e	Effective suspension-line length
l_R	Length of riser
L_r	Length of reefing line (installed length)
l_s	Length of suspension line
l_T	Distance between parachute canopy and forebody
M	Mach number, moment, system mass
M_s	Margin of safety
m	Mass
N	Any number
N_G	Number of canopy gores
N_R	Number of risers
N_{SL}	Number of suspension lines
N_c	Number of parachutes in a cluster
n	Strength loss factor due to water absorption
p	Pressure, strength of material
Δp	Pressure differential
q	Dynamic pressure
R	Reliability factor
Re	Reynold's number
R_m	Mass ratio
R_w	Weight ratio
r	Radius
S	Area, general
S_F	Safety factor
S_f	Footprint area
S_g	Area of canopy gore
S_o	Surface area of parachute canopy including vent and slots
S_p	Projected frontal canopy area
S_r	Total open area of slotted canopy
s	Factor for asymmetrical canopy loading
s_d	Deceleration distance
s_f	Filling distance of parachute
T	Temperature, thrust
t	Time (general)

t_f	Parachute filling time
u	Strength loss due to seam connections
V	Volume
v	Velocity (general)
v_e	Equilibrium velocity, rate-of-descent
v_H	Horizontal velocity
v_V	Vertical velocity
v_s	Velocity at line stretch (canopy stretch)
v_T	Trajectory velocity
W	Weight, general
W_P	Weight of parachute
W_{PA}	Weight of parachute assembly
W_R	Weight of parachute recovery system
w	Unit weight
x_1	Opening force reduction factor

Greek

α	Angle of attack as related to airflow
β	Angle of yaw, gore vertex angle
γ	Ratio of specific heat
Δ	Small increment of difference
δ	Angle between radials and suspension lines
ϵ	Relative elongation, drag area ratio $(C_DS)_R/(C_DS)_o$ = reefing ratio
η	Efficiency
θ	Angle of flight path from horizontal
$\varkappa$	Spring constant
λ	Porosity or air permeability of parachute canopy
λ_g	Geometric canopy porosity
λ_m	Porosity of canopy material
λ_T	Total porosity of parachute canopy
μ	Viscosity, constructed angle between canopy radials and horizontal
ν	Kinematic viscosity
ξ_g	Ratio of gravitational acceleration (g/g_o)
ϱ	Mass density of air
ϱ_o	Air density at sea level
Σ	Summation
σ	Air density ratio (ϱ/ϱ_o)
τ	Reefing line ratio, strength loss factor due to temperature
ϕ	Angle between suspension lines and longitudinal axis
ϕ_c	Angle between individual parachutes and cluster axis
$\sim$	Approximately
$\approx$	Approximately equal to
$\equiv$	Identical to

Abbreviations

D.B.	Deployment bag
Btu	British thermal unit
D.C.	Drogue chute
DR	Disreef
DOF	Degrees of freedom
EAS	Equivalent air speed
FFT	Free-flight tests
FIST	Aeronautical Institute at the University Stuttgart
IAS	Indicated air speed
M.P.	Main parachute
min	Minimum
MSL	Mean sea level
P.C.	Pilot parachute
psf	Pounds per square foot
P.P.	Parachute pack
psi	Pounds per square inch
R.I.P.	Ramair inflated parachute
RPV	Remotely piloted vehicle
SI	System International (International System of Units)
TAS	True airspeed
UVS	Unmanned vehicle system
WTT	Wind tunnel tests

3.5 List of References

3.1 *The International System of Units (SI)*, National Bureau of Standards Special Publication 330, issued December 1981, Superintendent of Documents, Government Printing Office, Washington, D.C. 20402.

3.2 *Metric Practice Guide*, March 1970, ASTM Designation E-380-70, American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

3.3 Lionel S. Marks, *Mechanical Engineers Handbook*, McGraw Hill Book Company.

3.4 *US Standard Atmosphere, 1976*, published by National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, United States Air Force, Superintendent of Documents Stock No. 003-017-00323-0, Government Printing Office, Washington, D.C. 20402.

Chapter 4
AERODYNAMICS AS RELATED TO PARACHUTES

Chapter 4 discusses the atmosphere in which parachutes operate and presents the basic aerodynamics relevant to the analysis and performance calculations of parachute recovery systems. This chapter includes the following sections: 4.1, Properties of the Atmosphere, a discussion of the environment surrounding the earth in which parachutes operate; 4.2, Continuity Law and Bernouli Equation, which govern the flow of gases around moving bodies; 4.3, Newton's Three Laws, which deal with forces and movement of bodies; 4.4, Forces Acting on a Body Moving Through Air; 4.5, Equilibrium of Forces in Steady Descent or Flight; 4.6, Wind Tunnel Testing of Parachutes, an important tool in parachute research and in the development of parachute recovery systems; and 4.7, List of References.

4.1 Properties of the Atmosphere

All forces acting on parachutes and all movements of parachutes are affected by the atmosphere, or air, surrounding the earth. The air at the earth's surface consists of approximately 78 percent nitrogen, 21 percent oxygen, and one percent of a mixture of such gases as argon, neon, helium, water vapor, carbon dioxide, and others. This chemical composition remains relatively constant to an altitude of about 160,000 feet (50 kilometers). The following air qualities are of major significance in the dynamics of bodies moving in the atmosphere:

Air quality	Symbol	Dimension
Specific weight of air	w	lb/ft^3, kg/m^3
Static pressure	p	atm, psf, Pa, bar, torr
Temperature	T	°F, °C
Air density	ϱ	$slugs/ft^3$, $kg\ s^2/m^4$
Gravity	g	ft/s^2, m/s^2
Speed of sound	C_s	ft/s, m/s

All of these qualities are altitude-dependent and may vary slightly on the earth's surface with geographic latitude. This is due to variations of the earth's radius caused by the centrifugal forces of the earth's rotation. All standard data used herein refer to a latitude of 45 degrees. Sea level is defined as Mean Sea Level (MSL). To compare performance data on an equal basis, the United States Bureau of Standards has defined standard day conditions as follows:

Temperature = 15°C or 59°F
Pressure = 760 mm Hg or 29.9213 in. Hg.

4.1.1 Specific Weight of Air

For standard day conditions of 59°F temperature and a pressure of 29.9213 in. Hg, the specific weight of air, w, is 0.07648 lb/ft^3 or 1.2250 kg/m^3. The specific weight of air changes with pressure, temperature, and humidity. Further data can be found in References 3.4 and 4.1, and in technical handbooks.

4.1.2 Static Pressure

Static pressure depends on geographic latitude, weather conditions, and altitude. The static pressure at any altitude results from the weight of the air above that altitude. For mean sea level (MSL) and standard day conditions, the pressure, p_o, is 29.9213 in. Hg = 760 mm Hg = 1.0 atmosphere. For conversion to pascal, torr or bar, see the conversion tables in Section 3.2.

4.1.3 Temperature

Temperatures are defined in the English and the S.I. (metric) system in the so-called absolute scale and the engineering scale. The absolute temperature minimum at 0 degrees pressure is: zero degrees kelvin = −273.16 degrees Celsius and zero degrees Rankine = −459.69 degrees Fahrenheit. This is also written:

Degrees kelvin = degrees Celsius +273.16
Degrees Rankine = degrees Fahrenheit +459.69.

The freezing point of water is 32 degrees Fahrenheit or zero degrees Celsius. The boiling point of water is 212 degrees Fahrenheit or 100 degrees Celsius.

4.1.4 Mass Density of Air

Mass density defines the amount of mass contained in a unit volume of air. The mass density of air, ϱ, is of special importance in aerodynamic calculations:

$$\varrho = \frac{\text{specific weight of air, w}}{\text{acceleration of gravity, g}} = \frac{\text{lb/ft}^3}{\text{ft/s}^2} = \text{slug/ft}^3$$

$$\text{slug} = \frac{\text{weight}}{\text{acceleration of gravity}} = \frac{\text{lb}}{\text{ft/s}^2}$$

Frequently, the density ratio, σ, is used:

$$\sigma = \frac{\text{ambient air density, } \varrho}{\text{standard sea level desntiy, } \varrho_o}$$

The factor, $1/\sqrt{\varrho/\varrho_o}$, determines the increase in parachute rate-of-descent with altitude. It is practical to remember that the density at 40,000 feet is one-quarter of the sea level density, and the density at 100,000 feet is one seventy-fifth of the MSL density. Therefore, the parachute rate-of-descent is about twice as high at 40,000 feet altitude and about nine times as high at 100,000 feet.

4.1.5 Gravity

Any mass attracts another mass with a force called gravity. If the earth were surrounded by a vacuum, a body suspended above the earth and released would fall toward the center of the earth with increasing velocity, caused by the acceleration of gravity, g. In reality, the falling body is decelerated by its air drag until the air drag, D, equals the weight of the body, W, and an equilibrium velocity is reached; for parachutes, this is called the steady-state rate-of-descent.

The acceleration of gravity, g, at sea level is

$$g = 32.174 \text{ ft/s or } 9.80665 \text{ m/s.}$$

The value, $g = 9.80665$ m/s, is standardized internationally but is accurate only for a latitude of 45 degrees.

With increasing altitude above the earth's surface, the acceleration of gravity, g, decreases in accordance with the equation

$$g = g_o\left(\frac{r}{r + h}\right)^2$$

where

g = acceleration of gravity at any altitude, ft/s^2
g_o = acceleration of gravity at sea level, ft/s^2
r = average earth radius = $2.08556 \cdot 10^7$ feet
h = altitude above sea level, feet

For other planets and heavenly bodies the acceleration of gravity varies with the mass of the body. For example, the acceleration of gravity on the planet Mars is about one-third of the acceleration of gravity on earth. For more details on planets and heavenly bodies, see page XII of Reference 2.1 and the appropriate literature.

4.1.6 Kinematic Viscosity

The coefficient of viscosity, μ, defines the sheering stresses in a gas or liquid and is sometimes called the resistance to continuous deformation. In aerodynamics, the coefficient of viscosity is combined with the mass density to form the kinematic viscosity, ν, where

$$\nu = \frac{\text{coefficient of viscosity, } \mu}{\text{mass density, } \varrho} = 0.0001576 \text{ ft}^2\text{/s at sea level}$$

The kinematic viscosity, ν, is altitude dependent and is used to calculate the Reynolds number, Re (see Reference 3.4).

4.1.7 Reynolds Number

The Reynolds number, Re_1, defines the relationship of mass forces to viscous friction forces in liquids and gases. It is calculated as

$$Re = \frac{v \cdot l}{\nu} = \frac{\text{velocity (ft/s)} \cdot \text{characteristic length (ft)}}{\text{kinematic viscosity (ft}^2\text{/s)}}$$

Reynolds number is an important criterion in subsonic, noncompressible flow, and allows comparison of model tests with full-scale flight tests. A Reynolds number effect on parachutes working in separated, turbulent flow has not yet been established, as shown in Chapter 5. The following chart shows the differences in Reynolds numbers for various air vehicles.

Subject	Insect	Glider	DC-3	B-747	Drogue chute	Main parachute	WTT model
R	$6 \cdot 10^3$	$2.5 \cdot 10^6$	$24 \cdot 10^6$	$100 \cdot 10^6$	$50 \cdot 10^6$	$20 \cdot 10^6$	$2 \cdot 10^6$

4.1.8 Mach Number

Mach number is an important parameter of supersonic flight; it states how much faster than the speed of sound the air vehicle travels.

$$\text{Mach number, M} = \frac{\text{flight velocity, v}}{\text{speed of sound, } c_s}$$

The speed of sound is the velocity at which a pressure disturbance, such as the sound of the human voice, travels in any medium. The speed of sound varies considerably in different gases, liquids, and metals:

Speed of sound in air at MSL	c_s = 1,116.46 ft/s = 340.38 m/s
Speed of sound in water	c_s = 4749 ft/s = 1461.21 m/s
Speed of sound in iron	c_s = 16,410 ft/s = 5710.7 m/s

The speed of sound depends on temperature and the chemical composition of the medium. A widely used equation for speed of sound in air is:

$$c_s = 41.4 \sqrt{\gamma \cdot T}$$

where

c_s = speed of sound in dry air, ft/s
γ = ratio of specific heat, equal to 1.4 for dry air, dimensionless
T = temperature in Fahrenheit absolute, equal to 549.67 + °F

The speed of sound changes with altitude similar to the change in temperature, as shown in Chapter 3, Figure 3-1. The drag of streamlined bodies, such as missiles, airfoils, and airplanes, increases considerably as their velocities approach Mach one. Depending on the configuration of the body, supersonic compressibility effects may occur in the 0.75 to 0.85 Mach range, causing local supersonic flow, shock waves, flow separation, and concomitant increases in drag and changes in stability.

Parachutes that operate in separated flow over the entire velocity range do not show the typical drag increase when operating close to or beyond Mach one. Supersonic parachute behavior is discussed in detail in Chapter 5.

4.2 Continuity Law and Bernoulli Equation

4.2.1 Continuity Law

Air is thought to flow in layers called streamlines. Figure 4-1 shows streamlines as layers of air without air transfer between individual layers and, with the air being incompressible, an assumption that is valid for subsonic flow.

FIGURE 4-1. Typical Streamline.

If exchange of air does not occur across the streamline boundaries, then the amount of air entering the streamline at point 1 must also exit at point 2, as shown on Figure 4-1. Since the cross section at point 2 is smaller than the cross section at point 1, the air must exit at a higher velocity. The following equation defines this condition:

$$v_1 \cdot S_1 \cdot \varrho = v_2 \cdot S_2 \cdot \varrho$$

where

S = cross section of the streamline
v = velocity in the streamline
ϱ = density of the air flowing in the streamline

This equation, which governs the flow in and around a body in gases and liquids, is important in aerodynamics and is called the "Continuity Law." For incompressible subsonic flow, it can be simplified to:

$$v_1 \cdot S_1 = v_2 \cdot S_2$$

Whenever the cross section narrows, the velocity increases; when the cross section widens, the velocity decreases.

4.2.2 Bernoulli Equation

Figure 4-2 illustrates a streamline with the cross section, S, the velocity, v, and the pressure, p. If the air is incompressible, the velocity, v, downstream is $v + \Delta v$ and the pressure $p + \Delta p$. If the air is inviscid, the inertia forces caused by the acceleration of air from v to $v + \Delta v$ must be balanced by differential pressure forces.

The following equation can be written:

$$p \cdot S - (p + \Delta p)S = m \cdot \frac{dv}{dt}$$

Simplified, the above equation yields

$$dp = -\varrho v \, dv$$

and

$$p = -1/2 \, \varrho v^2 + C$$

The above equation allows the following consideration. If p is pressure, then $1/2 \, \varrho v^2$ and C must also be pressure. The equation $1/2 \, \varrho v^2$ includes a velocity and is referred to as the dynamic pressure or sometimes as velocity or impact pressure. Pressure, p, is defined as static pressure, $1/2 \, \varrho v^2$ as dynamic pressure, and the sum of both, C, is the total pressure:

or

$$p + 1/2 \varrho v^2 = H$$

and

$$p_1 + 1/2 \, \varrho v_1^2 = p_2 + 1/2 \varrho v_2^2$$

where H is the total pressure of the system, psf.

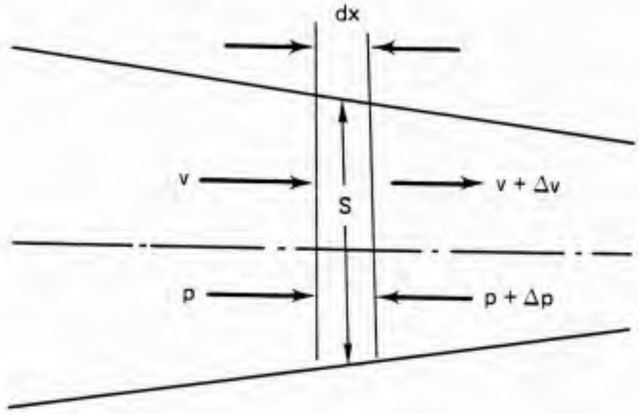


FIGURE 4-2. Pressure and Velocity Distribution in a Streamline Element.

Dynamic pressure is a frequently used quantity in aerodynamics and has been assigned the symbol, q, so

$$q = 1/2\varrho v^2$$

where

q = dynamic pressure, psf
ϱ = air density, slugs/ft^3
v = velocity at a point of undisturbed flow, ft/s

The following formulas are used for calculating dynamic pressure if the velocity is given in ft/s, knots, mph, or km/h, respectively:

$$q = \frac{v^2}{841.4} \text{ (ft/s)}, \quad q = \frac{v^2}{295} \text{ (knots)}, \quad q = \frac{v^2}{391.2} \text{ (mph)}, \quad q = \frac{v^2}{1013.1} \text{ (km/h)}$$

4.3 Newton's Three Laws of Motion

Engineering mechanics are governed by the following three laws of Isaac Newton.

1. A body remains at rest or in an unaccelerated state of motion unless acted upon.

2. A force acting upon a body will produce an acceleration in the direction of the force.

3. An action in one direction will produce an equal reaction in the opposite direction.

The first law is self-explanatory. The second law may be expressed by the equation

$$F = m \cdot a$$

where

F = force in pounds acting on the mass, m
m = mass of the body that the force is acting upon, slugs
a = acceleration in ft/s^2 resulting from the force, F

The mass, m, of a body is obtained by

$$m = \frac{W}{g}$$

where

W = weight of the body, lb
g = acceleration of gravity, ft/s^2

The mass, therefore, has the dimension of

$$m = \frac{W}{g} = \frac{lb}{ft/s^2}$$

This unit of mass is the slug.

The equation of Newton's second law can now be written in the form

$$F = \frac{W}{g} \cdot a \text{ , or } F = W\frac{a}{g} \text{ .}$$

The factor, a/g, is frequently called the load factor, G, and tells how much larger a force is than a force equivalent to the weight of the body. It is customary in parachute work to state that the maximum parachute force allowed is $G \cdot W$ or $(a/g) \cdot W$. It is appropriate to write:

Maximum allowable parachute force, $F = W\frac{a}{g}$, or $F = W \cdot G$.

Figure 4-3 illustrates Newton's third law, explaining the principle of the rocket which can produce thrust in a perfect vacuum.

A mass, m, ejected from a rocket at the velocity, v, per unit time, t, will produce a force, F, which in turn creates a reaction force, R, of equal magnitude but acting in the opposite direction.

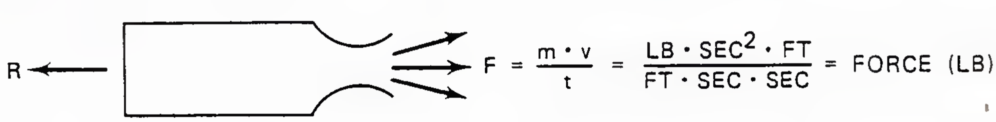


FIGURE 4-3. Rocket Principle.

4.4 Forces Acting on a Body Moving Through Air

4.4.1 Symmetrical Body

A body moving through air experiences forces caused by air pressure acting on the body. The same forces exist if the body moves through air, such as a descending parachute, or if the body is fixed and the air moves against the body, such as a parachute or an airfoil in a wind tunnel, as shown in Figure 4-4.

A stable parachute in a wind tunnel experiences only the force called "drag" in the direction of the air flow. This drag force, D, is calculated:

$$D = q \cdot S \cdot C_D$$

where

D = drag, lb
q = dynamic pressure, psf
S = total surface area of the parachute canopy, ft^2
C_D = coefficient of drag, dimensionless

The dynamic pressure, q, can be calculated from Section 4.2.2. The surface area of the canopy, S, is selected as a reference area. The drag coefficient, C_D, is a form factor that indicates the drag characteristic of a specific shape. Most aerodynamic bodies are designed for low drag or a low drag coefficient. Parachutes, generally, are designed for high drag; therefore, à high drag coefficient is desirable. This difference in drag is demonstrated by the two bodies shown in Figure 4-5.

Both bodies have the same cross section in the direction of the airflow. The cylindrical, streamlined body has a smooth airflow over its total body length, resulting in a drag coefficient, C_D = 0.05 to 0.1, depending on slenderness ratio, surface roughness, and shape. The drag coefficient of all streamlined bodies is much affected by Reynolds number and Mach number. The open hemisphere, which is similar to a parachute canopy, has a drag coefficient, C_D, of 1.3 to 1.4 for the same body cross section. The difference in drag is explained by the smooth airflow around the streamlined body and the separated, turbulent flow around the open hemisphere. The drag of bodies with separated flow, like parachute canopies, is little affected by Reynolds number.

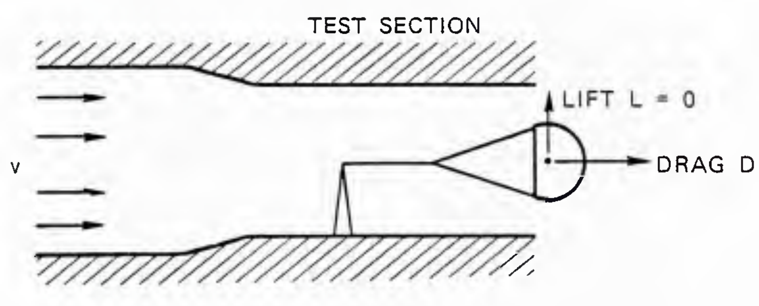


FIGURE 4-4. Stable Parachute in a Wind Tunnel.

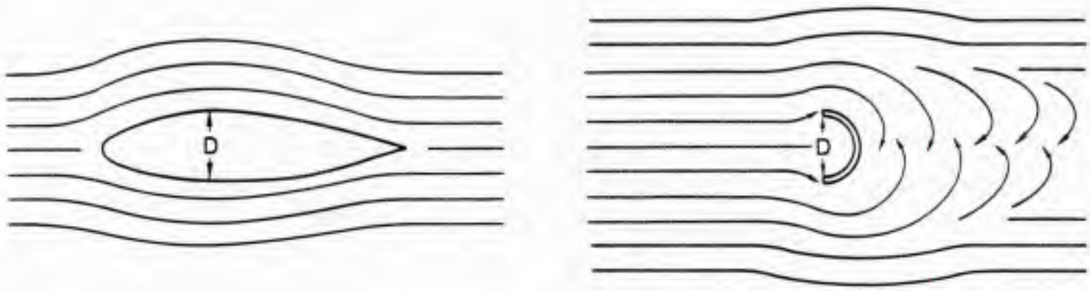


FIGURE 4-5. Airflow Around a Streamlined Body and an Open Hemisphere.

4.4.2 Air Flow Around an Asymmetrical Body (Airfoil)

Figure 4-6 shows an airfoil fixed at an angle of attack, α, against the airflow in a wind tunnel. This airfoil creates a drag force, D, in the direction of the flow; a lift force, L, perpendicular to the direction of the flow; and a moment, M, around the attachment point of the airfoil. The sign convention of moments and forces shown are positive. Lift and drag can be combined for the resultant force, R.

The lift, L, is calculated to:

$$L = q \cdot S \cdot C_L$$

where

L = measured lift, lb
q = dynamic pressure, psf
S = reference area, ft^2
C_L = lift coefficient, dimensionless

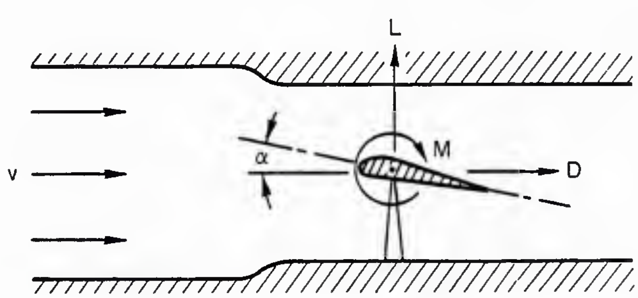


FIGURE 4-6. Wind Tunnel Forces Acting on an Airfoil.

The moment is:

$$M = q \cdot S \cdot c_m \cdot c$$

where

M = moment, ft-lb
q = dynamic pressure, psf
S = reference area, ft^2
c_m = moment coefficient, dimensionless
c = average chord width of the wing, ft

The reference area, S, is defined by agreement. For streamlined bodies, the maximum body cross section is used. Airfoils use the planform of the wing, and parachutes the canopy surface area. There are practical reasons for the selection of the wing planform and the parachute surface area as references. The wing planform for a specific wing is fixed, whereas the cross section of the wing in the direction of the flow changes with the angle of attack. Similarly, the surface area of the parachute canopy is fixed; however, the frontal projected area of the inflated parachute canopy changes with airspeed, porosity, line length, and type of parachute.

Forces and moments acting on an airfoil or a parachute canopy may be presented in several ways. The two most frequently used methods, as shown in Figure 4-7, are with forces oriented to the axis of flight and with forces oriented to the axis of the airfoil.

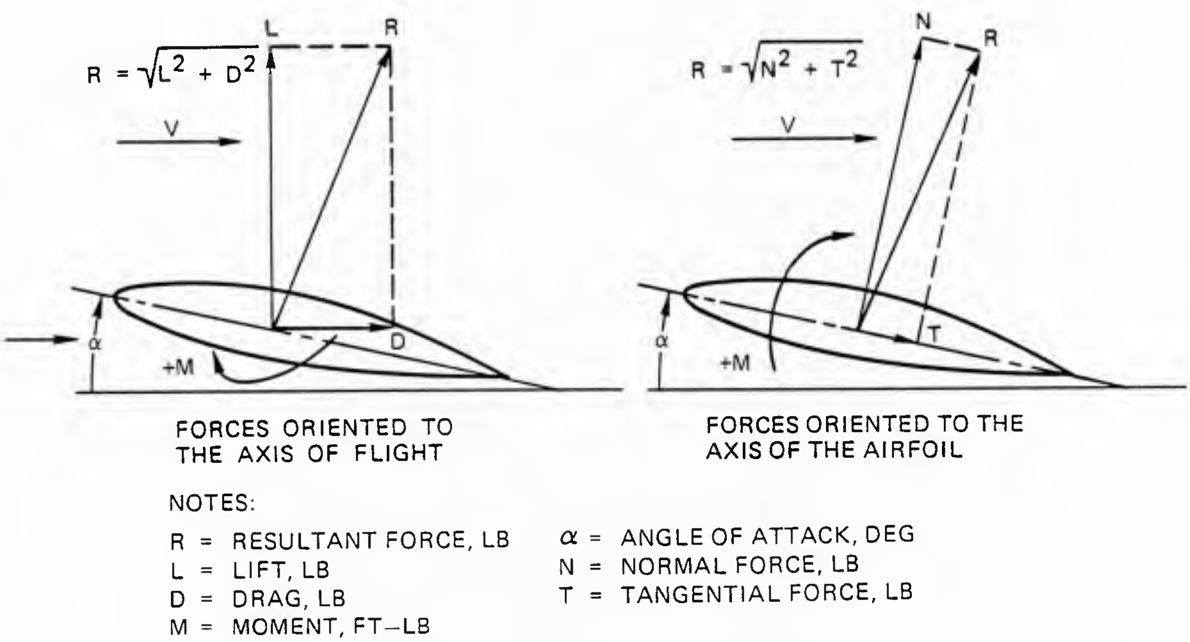


FIGURE 4-7. Aerodynamic Forces Acting on an Airfoil.

The tangential force, T, and the normal force, N, are calculated by:

$$T = C_T \cdot S \cdot q$$

and

$$N = C_N \cdot S \cdot q$$

where

C_T = tangential force coefficient, dimensionless
C_N = normal force coefficient, dimensionless

The resultant force, R, and the moment, M, in both presentations have the same direction and the same magnitude. The airflow fixed system is preferred for aerodynamic performance calculations, and the airfoil fixed system for wing stress calculations. The aerodynamic coefficients C_L, C_D, C_T, C_N, and C_m can easily be determined in wind tunnel measurements.

Figure 4-8 shows the relationship of both force systems on a parachute. By definition, a negative moment is stabilizing, as illustrated in Figure 4-8. It is of interest to note that in Europe the stabilizing moment is defined as positive. Wind tunnel installations frequently measure normal and tangential force instead of lift and drag. Knowing α, T, and N, the drag, D, can be calculated by:

$$\text{Drag } D = T \cdot \cos \alpha + N \cdot \sin \alpha$$

For a parachute with an angle of attack, α, equal to zero, the drag force and the tangential force are equal.

Figure 4-9 shows the coefficients C_T, C_D, and C_m versus angle of attack for stable and unstable parachutes.

The coefficient presentation shows two interesting facts. The slope of the moment coefficient curve, dC_m/d_α, for the unstable parachute is positive between −25 degrees and +25 degrees; this is, by definition, destabilizing. This parachute will oscillate approximately 25 degrees. The slope of the moment coefficient, dC_m/d_α, for the stable parachute is negative over the total angle of attack; this is, by definition, stabilizing. The steeper the negative dC_m/d_α slope, the greater is the stabilizing tendency of the parachute, and the better is its damping capability against unstabilizing forces such as sudden gusts of wind.

Figure 4-10, from Reference 4.1, demonstrates the effect of airflow around a cylinder and an airfoil. The circulation around a rotating cylinder causes lift due to the increase in velocity on one side of the cylinder and a decrease on the opposite side. This is called the Magnus effect.

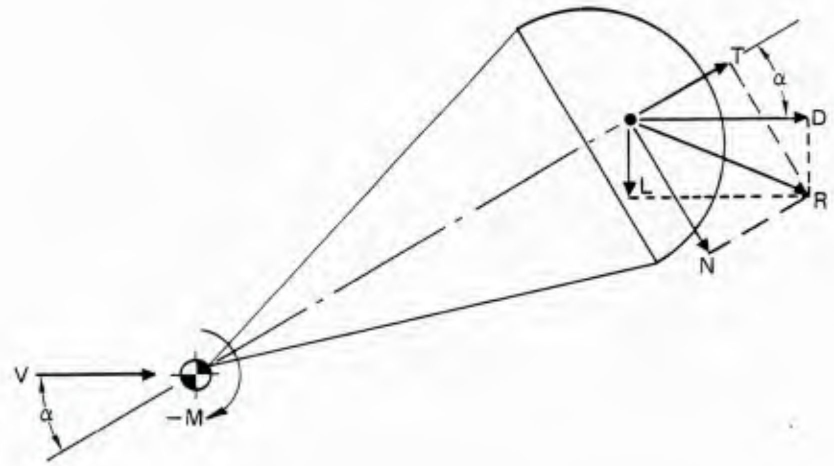


FIGURE 4-8. Forces Acting on a Parachute.

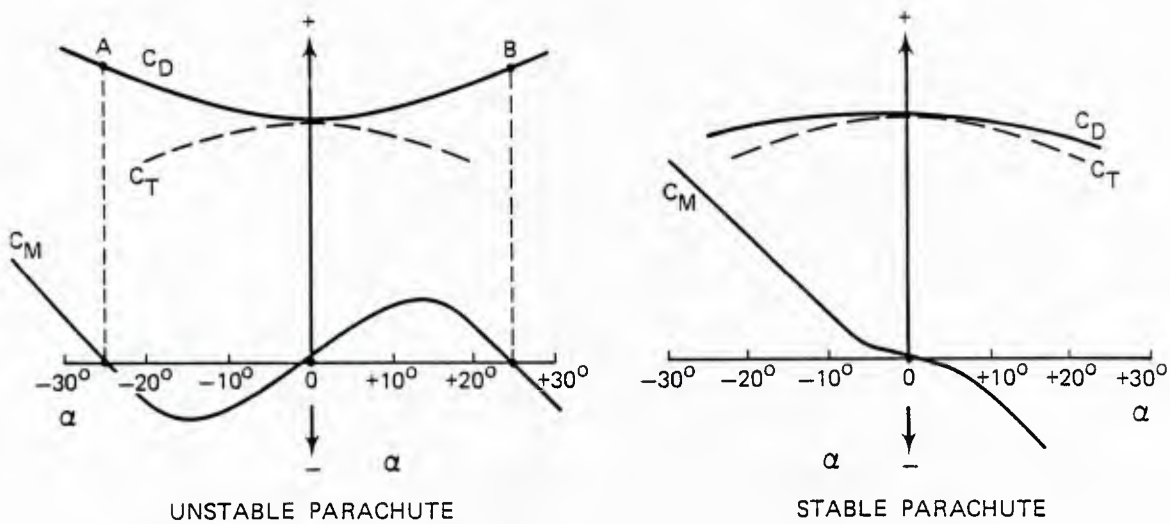


FIGURE 4-9. Coefficients C_D, C_T, and C_M Versus Angle of Attack, α, for a Stable and Unstable Parachute.

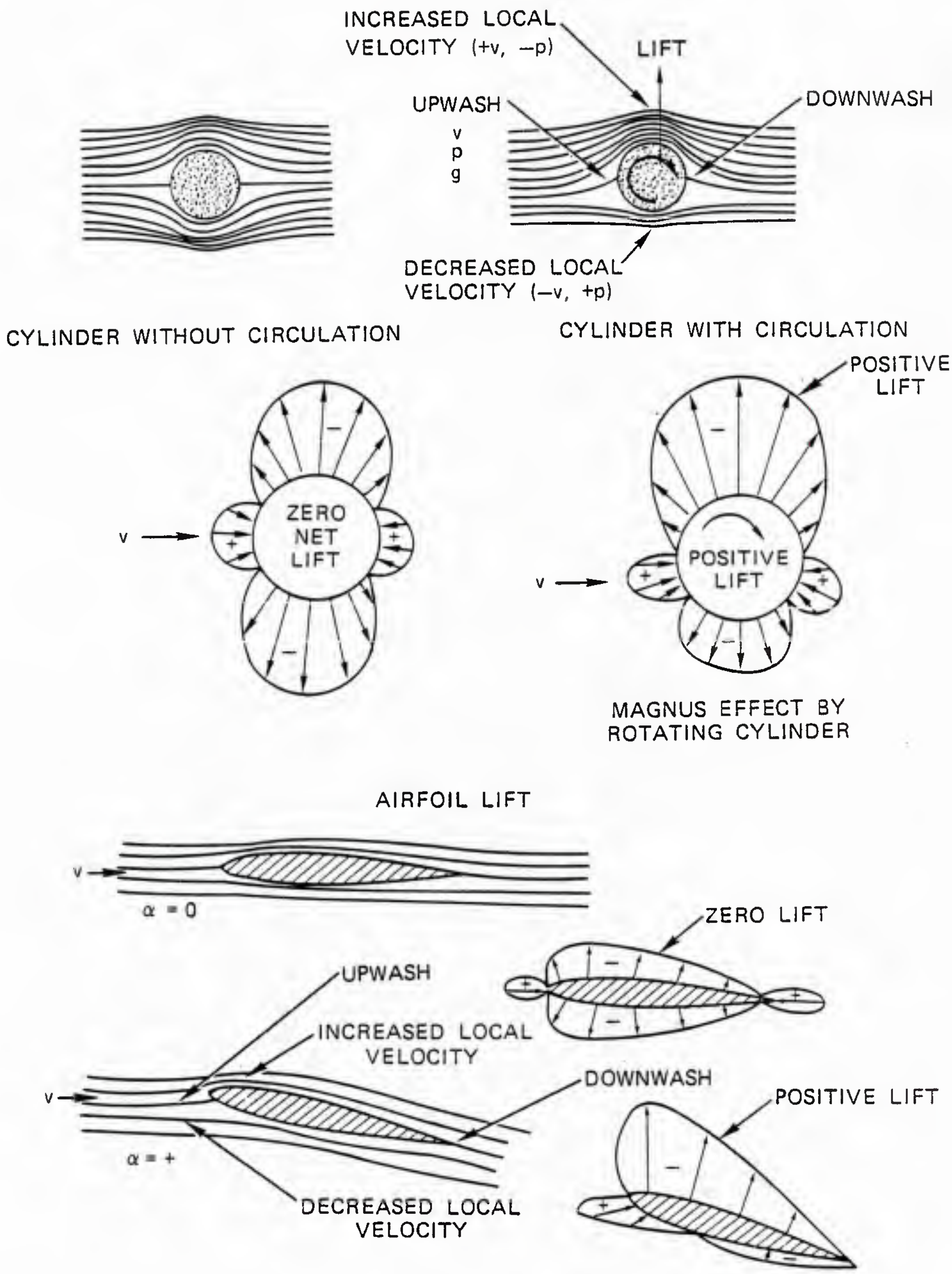


FIGURE 4-10. Effect of Airflow Around a Cylinder and an Airfoil.

4.5 Equilibrium of Forces in Steady Descent or Flight

4.5.1 Parachute in Steady Descent

A stable parachute in unaccelerated descent has an equilibrium between the total drag of the parachute and the load, D_T, and the weight of the load and the parachute assembly, W_T. This is shown in Figure 4-11. For steady descent:

$$D_T = W_T \qquad \text{or} \qquad D_p + D_L = W_p + W_L$$

where

D_T = total drag, lb
D_p = drag of parachute, lb
D_L = drag of load, lb
W_T = total weight, lb
W_p = weight of parachute, lb
W_L = weight of load, lb

In most cases, the drag of the load can be neglected in relation to the large drag of the parachute. With drag, $D = C_D \cdot S \cdot \varrho/2 \cdot v^2$ and $D_T = W_T$, and solving for v, the important equation for rate-of-descent, v_e, is obtained.

Rate-of-descent,

$$v_e = \sqrt{\frac{2W}{S \cdot C_D \cdot \varrho}}$$

or in parachute terminology for rate-of-descent at sea level,

$$v_{e_o} = \sqrt{\frac{2W_T}{S_o \cdot C_{D_o} \cdot \varrho_o}}$$

and rate-of-descent at any altitude,

$$v_e = \sqrt{\frac{2W_T}{S_o \cdot C_{D_o} \cdot \varrho_o}} \cdot \frac{1}{\sqrt{\varrho/\varrho_o}}$$

For $1/\sqrt{\varrho/\varrho_o}$, see column 4 in Table 3-3, Chapter 3.

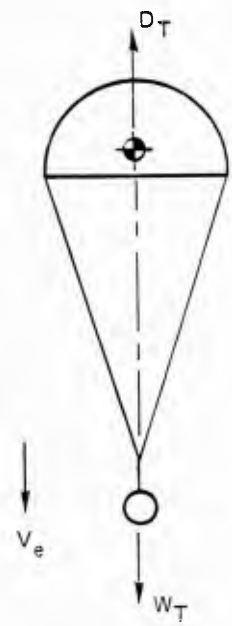


FIGURE 4-11. Forces Acting on a Parachute in Steady Descent.

In the equation for rate-of-descent, v_e,

W_T = weight of load and parachute assembly, lb
S_o = canopy surface area, ft^2
C_{D_o} = parachute drag coefficient related to S_o
ϱ = air density at a specific altitude in $slugs/ft^3$, as shown in Table 3-3.

During descent from altitude, the parachute system is constantly decelerated due to the increasing air density. This can be ignored for slowly descending main parachutes. However, for drogue chute systems that descend at 200 ft/s and more, the constant deceleration may result in velocities three to five percent higher than the steady rate-of-descent.

4.5.2 Gliding Parachutes

Figure 4-12 shows the balance of forces on a gliding parachute. The total weight of the system, W_T, must be balanced by the resultant force, R. However, a lifting force is required for glide. To satisfy the force balance,

$$R = W_T ,$$

$$R = C_R \cdot S \cdot \varrho/2 \cdot v^2 ;$$

and

$$R = \sqrt{L^2 + D^2} ,$$

$$C_R = \sqrt{C_L^2 + C_D^2}$$

Solving for trajectory velocity, v_T,

$$V_T = \sqrt{\frac{2W}{S \cdot \varrho}} \cdot \sqrt{\frac{1}{C_L^2 + C_D^2}}$$

or

$$V_T = \sqrt{\frac{2W}{S \cdot \varrho}} \cdot \frac{1}{C_R}$$

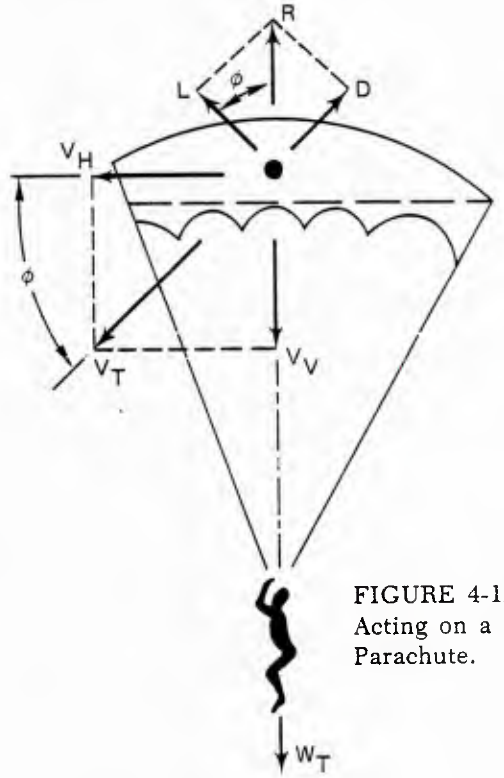


FIGURE 4-12. Forces Acting on a Gliding Parachute.

and horizontal velocity, $V_H = V_T \cdot \cos \alpha$, and vertical velocity, $v_V = v_T \cdot \sin \alpha$.

The glide ratio is obtained from

$$\tan \phi = L/D = V_V/V_H = C_L/C_D.$$

Analysis of Figure 4-12 indicates that the larger the ratio of lift to drag, the better the glide ratio, L/D. A high resultant coefficient, C_R, results in a low glide or trajectory velocity, V_T, desirable for landing. A small C_R results in a high glide velocity, V_T, which is desirable for flying toward a target, compensating for head winds, or covering a distance quickly. Generally, gliding parachutes act like and follow the same aerodynamic rules as low-aspect-ratio wings.

4.5.3 Parasite Drag and Induced Drag

The drag acting on a lift-producing air vehicle, such as a gliding parachute or an aircraft, has two primary components, the parasite drag, D_p, and the induced drag, D_i.

Parasite drag is produced by the form drag from individual components, such as the suspension lines, the canopy, and the jumper of a gliding parachute; and the fuselage, tail section, and control surfaces of an airplane. Large surfaces produce surface friction drag as part of the parasite drag.

Induced drag is caused by the lifting action of the parachute canopy or the aircraft wing. A detailed discussion of induced drag can be found in the references in Section 4.7. Total drag, D_T, can thus be defined as:

$$D_T = D_p + D_i$$

or in coefficient form

$$C_{D_T} = C_{D_p} + C_{D_i}$$

The parasite drag, D_p, and the coefficient, C_{D_p}, can be determined in wind tunnel tests, or calculated as the sum of the individual component drag.

The induced drag coefficient, C_{D_i}, of a gliding parachute canopy or a wing profile can be calculated to:

$$C_{D_i} = \frac{C_L^2 \cdot S}{\pi \cdot b^2}$$

where

C_{D_i} = coefficient of induced drag, dimensionless
C_L = lift coefficient, dimensionless
S = surface reference area, ft^2
π = number equal to 3.1415
b = span of the wing or parachute, ft

The expression b^2/S is defined as the aspect ratio of a wing or parachute with the notation $AR = b^2/S$.

Therefore,

$$C_{D_i} = \frac{C_L^2}{\pi \cdot AR}$$

The equation for induced drag indicates that increasing the aspect ratio, AR, reduces the induced drag coefficient, C_{D_i}, and therefore the drag, D. This, in turn, increases the glide ratio, L/D. Increasing the glide ratio by increasing the aspect ratio is optimized on high-performance sailplanes with aspect ratios in excess of 20. Increasing the glide ratio of gliding parachutes by increasing the aspect ratio has limitations which are discussed in Chapter 5.

4.5.4 Aircraft in Horizontal Flight

Figure 4-13 shows forces and moments on an aircraft in steady, horizontal flight.

In steady, horizontal flight an equilibrium exists between all forces and moments acting on the aircraft. Lift on the wing and tail, L_W and L_T, and the weight of the aircraft, W_A, balance in the vertical plane. Thrust, T, and drag, D, balance in the horizontal plane, and the positive or negative moment, M, is balanced by the positive or negative lift of the tail multiplied by the moment arm, L_T.

Any imbalance in these forces results in descent or climb in the vertical plane, and faster or slower speed in the horizontal plane. A change in the lift of the elevator initiates climb or descent. Thrust, T, is the prime contributor for climb or descent and faster or slower speed. However, a balance of forces must always be maintained for horizontal flight or steady rate-of-climb or descent.

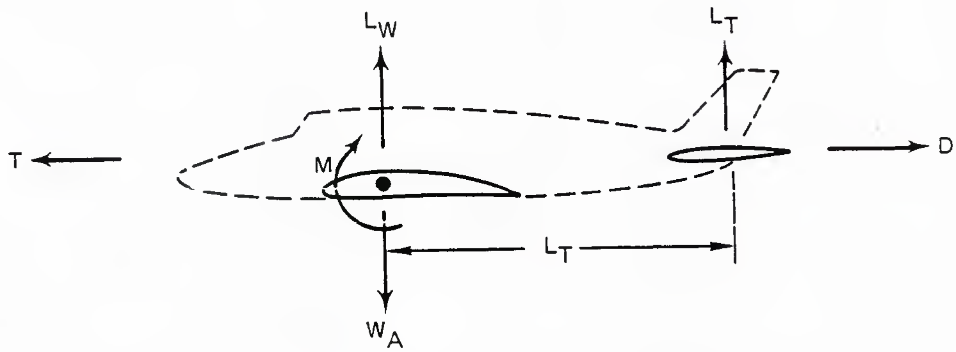


FIGURE 4-13. Forces and Moments Acting on an Aircraft in Steady Flight.

4.6 Wind Tunnel Testing of Parachutes

Wind tunnels are an effective tool for testing air vehicles and air vehicle components, and have been used successfully for testing parachutes and parachute systems. Experience has shown that certain rules apply for the wind tunnel testing of parachutes. Small parachutes manufactured from textiles cannot be made sufficiently similar to large parachutes in geometric design and flexibility. Lightweight material, required to obtain design similarity, is difficult to manufacture or is unobtainable.

4.6.1 Blowers

The simple air blower shown in Figure 4-14 is a proven tool for preliminary parachute testing of a chiefly qualitative nature. Unless special test conditions prevail, parachutes tested should be a minimum of 1.5 to 2.0 feet in diameter to obtain meaningful results.

One cardinal rule has been established over many years of parachute wind tunnel testing:

> Changing the performance of a model parachute in wind tunnel testing (for example, changing the drag characteristics of a model parachute by installing a drag skirt) will cause a similar change, percentagewise, in the drag of a large parachute using the same modification. This is also true for stability and opening force characteristics.

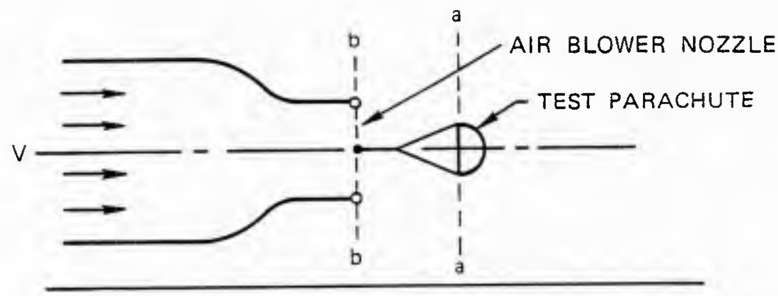


FIGURE 4-14. Typical Air Blower.

An air blower is a good preliminary test tool, permitting quick changes of parachute configuration and excellent visual observation.

4.6.2 Open-throat, No Return Wind Tunnels

The open-throat, no return wind tunnel shown in Figure 4-15 permits exact measurements if parachutes of sufficient size are used. Parachutes of three or more feet in diameter are well-suited for obtaining good, quantitative test results.

It is important to note that in air blowers and open-throat wind tunnels, the velocity at the skirt of the parachute, Section a-a of Figures 4-14 and 4-15, is lower than the velocity at the nozzle exit of the wind tunnel, Section b-b of Figures 4-14 and 4-15. Care must be taken to measure the parachute test velocity at Section a-a and not at Section b-b, the customary attachment point for airfoils and models.

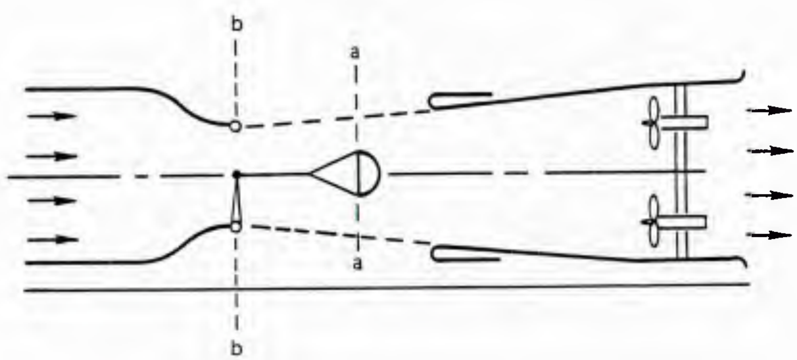


FIGURE 4-15. Open-throat, No Return Wind Tunnel.

Wind tunnels frequently cannot test at the descent velocity of most main parachutes of 20 to 30 feet per second. Obtaining proper test results at this low velocity is hampered by a poor velocity distribution in the wind tunnel test section, and by the weight of the test parachute. The latter has a tendency to pull the parachute downward, thereby providing a negative angle of attack. Testing unstable parachutes at higher velocities presents the problem that the drag coefficient, C_D, of unstable parachutes is velocity sensitive. This is described in Chapter 5.

An open-throat wind tunnel permits quick changes in parachute configuration, such as changing the suspension line and reefing line lengths. Large open-throat wind tunnels that are not sealed against outside elements suffer atmospheric problems such as fog formation in the test section.

4.6.3 Closed-throat, Full Return Wind Tunnel

Figure 4-16 shows the schematic drawing of a full return, closed-throat wind tunnel. This is generally considered the wind tunnel best suited for obtaining good, qualitative, aerodynamic data, since it has a uniform velocity distribution in the test section. Its disadvantage is that it is more difficult to gain access to the test section for changing the parachute configuration.

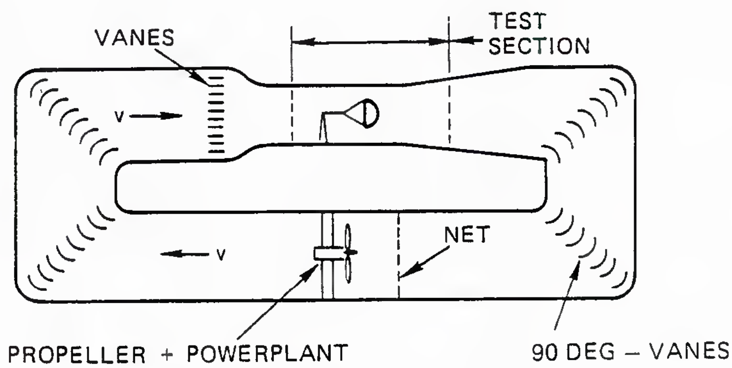


FIGURE 4-16. Closed-throat, Full Return Wind Tunnel.

4.6.4 General Comments for the Wind Tunnel Testing of Parachutes

a. Parachute models for wind tunnel testing should be as large as possible and as similar as possible in geometry and flexibility to full-scale parachutes. Parachutes of less than 1.5 feet in diameter generally lack geometric similarity and material flexibility, resulting in poor inflation characteristics and dissimilar inflated shapes.

b. The finished dimensions of model parachutes must be measured as accurately as possible to determine the nominal diameter, D_o, and the surface area, S_o. Model parachutes will shrink from five to ten percent during manufacture due to sewing take-up, resulting in a notable difference in the dimensions between the drawing and the completed article.

c. Wind tunnel tests of parachutes are excellent for comparing different models and modifications; also, they are the most effective means for measuring coefficients of lift, drag, and normal and tangential forces, as well as for determining the load coefficient, C_x, for infinite load.

d. In wind tunnel tests, velocity decay does not occur during parachute inflation and operation; this is defined as testing under "infinite mass condition." First stage drogue chutes, and parachutes with a canopy loading, $W/C_D \cdot S$ in excess of 100 psf, approach this condition. Low canopy-loading main parachutes with rates-of-descent of 20 to 30 ft/s have a large velocity decay during opening, requiring careful interpretation of the opening force data obtained in wind tunnel tests.

4.7 List of References

For readers interested in a more detailed study of aerodynamics, the following books are recommended.

4.1 H. H. Hurt, *Aerodynamics for Naval Aviators*, Navy Manual NAVWEPS 00 80T 80, Chief of Naval Operations, Aviation Training Division.

4.2 James H. Dwinnel, *Principle of Aerodynamics*, McGraw-Hill Book Company, New York, 1949.

4.3 John Morane, *Introduction to Theoretical and Computational Aerodynamics*, John Wiley & Sons, 1984.

4.4 Richard S. Shevell, *Fundamentals of Flight*, Prentice-Hall, 1983.

4.5 John D. Anderson, Jr., *Introduction to Flight, Its Engineering and History*, McGraw-Hill Book Company, New York, 1978.